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A Catch Per Unit Effort (CPUE) Spatial Metric with Respect to the Western North Atlantic Pelagic Longline Fishery

Max Appelman
Nova Southeastern University, ma1177@nova.edu

NOVA SOUTHEASTERN UNIVERSITY OCEANOGRAPHIC CENTER

A CATCH PER UNIT EFFORT (*CPUE*) SPATIAL METRIC WITH RESPECT TO THE WESTERN NORTH ATLANTIC PELAGIC LONGLINE FISHERY

By
Max H. Appelman

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Thesis Committee

Major Professor: ______________________________
David Kerstetter, Ph.D.

Committee Member: ______________________________
Brian Walker, Ph.D.

Committee Member: ______________________________
Bernhard Riegl, Ph.D.

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Abstract

Catch per unit effort (*CPUE*) is a quantitative method used to describe fisheries worldwide. *CPUE* can be presented as number of fish per 1000 hooks, number of fish per amount of fishing time, or with any unit of effort that best describes the fishery (e.g., search time, hooks per hour, number of trawls). *CPUE* is commonly used as an index to estimate relative abundance for a population. These indices are then applied within stock assessments so that fisheries managers can make justified decisions for how to manage a particular stock or fishery using options such as quotas, catch limitations, gear and license restrictions, or closed areas. For commercial pelagic longline (PLL) fisheries, onboard observer data are considered the only reliable data available due to the large-scale movements of highly migratory species (HMS) like tunas and because of the high costs associated with fisheries independent surveys. Unfortunately, fishery-reported logbook data are heavily biased in favor of the target species and the expense of onboard observers results in a low percentage of fleet coverage. Subsequently, *CPUE* derived from fishery-dependent data tends to overestimate relative abundance for highly migratory species. The spatial distribution of fish and fishing effort is essential for understanding the proportionality between *CPUE* and stock abundance. A spatial metric was created ($^{S}CPUE$) for individual gear deployments using observer-based catch and effort data from the western North Atlantic PLL fleet. $^{S}CPUE$ was found to be less variable than *CPUE* when used as an index of relative abundance, suggesting that $^{S}CPUE$ could serve as an improved index of relative abundance within stock assessments because it explicitly incorporates spatial information obtained directly from the fishing location. Areas of concentrated fishing effort and fine-scale aggregations of target and non-target fishes were identified using the optimized hot spot analysis tool in ArcGIS (10.2). This $^{S}CPUE$ method describes particular areas of fishing activity in terms of localized fish density, thus eliminating the assumption that all fish in a population are dispersed evenly within statistical management zones. The $^{S}CPUE$ metric could also assist fisheries management by identifying particular areas of concern for HMS and delineating boundaries for time-area closures, marine protected areas, and essential fish habitat.

Keywords: *CPUE*, pelagic longline, relative abundance, spatial distribution

Introduction

Catch per unit effort (*CPUE*) is a statistical method used to quantify the number of fish caught per unit of effort for a commercial fishing activity (Harley et al. 2001). *CPUE* can be represented as number of fish per 1000 hooks (the metric used for pelagic longline fisheries), number of fish per amount of fishing time (commonly used in trawl fisheries), or with any other unit of effort that best describes the gear type and the fishery (e.g., search time, number of hooks per hour, number of trawls, number of fish per square kilometer). *CPUE* is commonly used as an index to estimate relative abundance of a population (Harley et al. 2001, Maunder et al. 2006, and Lynch et al. 2012). Fisheries scientists take these indices of relative abundance and apply them within stock assessment models, which are then used by fisheries managers and policymakers to make justified decisions of how to manage a particular stock or fishery. Management actions are frequently expressed via a combination of catch quotas, catch limits, license restrictions and limitations, gear restrictions or modifications, and time-area closures often resulting in economic repercussions affecting the fishermen and consumers alike (Maunder *et al*. 2006).

Abundance estimates can only be as accurate as the data behind them, and *CPUE* has frequently been misinterpreted, resulting in relatively poor managerial decisions. A classic example is the collapse of the northwest Atlantic cod *Gadus morhua* in the late 1980s. Cod exhibit increasing schooling behavior as population decreases (Hutchings 1996). Because of this schooling behavior, consistently high *CPUE*s were maintained by bottom trawlers in this region from the 1960s through the mid-1980s, even though the stock was declining exponentially. Ultimately, the cod population was fished so low that the stock crashed and the North Atlantic U.S. commercial cod fishery closed in 1992 (Hutchings 1996). In this example, northwest Atlantic cod *CPUE* was disproportionately high in relation to stock abundance. Catch, essentially, can only be proportional to abundance if the catchability of all individuals in a population is constant. Since catchability is rarely constant throughout a population, raw *CPUE* is rarely proportional to abundance (Maunder et al. 2006). Variables effecting catchability include changes in fleet efficiency or fleet dynamics (Gillis and Peterman 1998), changes in target species, spatial and temporal effects (Nishida and Chen 2004) and most prominently, interactions between the fishing method and the target species population dynamics (Maunder et al. 2006). Specifically, fisheries dependent *CPUE* data only come from areas in which a fishery operates, providing no information on other areas inhabited by the target stock (Walters 2003). It is very common for a fishery to operate on only a fraction of a population's geographic range, especially for highly migratory species like tunnid tunas and swordfish *Xiphias gladius*. If non-fished areas are not addressed explicitly within *CPUE* analyses, then in the context of fisheries management, they are assumed to have the same characteristics (e.g., population abundance) as the fished areas. This oversight can lead to severely inaccurate abundance indices and subsequent poor management regimes (Walters 2003). Abundance estimates for commercially valued pelagic species like swordfish rely heavily on pelagic longline *CPUE* data, and these estimates usually do not explicitly incorporate spatial analysis.

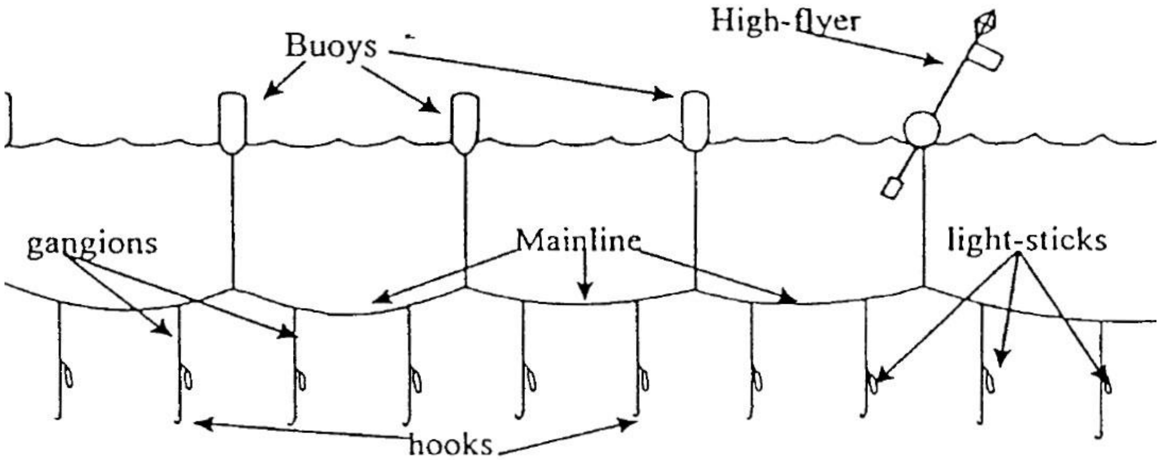
Characterizing pelagic longlines

Pelagic longline (PLL) gear is a commercial fish harvesting method that primarily targets species that undergo transoceanic seasonal migrations commonly referred to as highly migratory species (HMS) (FSEIC 1999). The PLL fishery in the western North Atlantic (WNA) primarily targets swordfish, yellowfin tuna *Thunnus albacares*, and bigeye tuna *Thunnus obesus*; however, other oceanic species (e.g., selected shark species and common dolphinfish *Coryphaena hippurus*) are targeted during various seasons (SAFE 2014). Modern PLL gear (Figure 1) typically consists of 20-30 miles of heavy monofilament mainline with baited drop lines, or gangions, attached at predetermined increments along the mainline (Watson and Kerstetter 2006). Using the appropriate combination of buoys and weights, fishermen deploy PLL gear from just below the sea surface to 350 m depths and leave the gear to passively fish (referred to as "soak time") for several hours to overnight before the gear is retrieved. Typically, a PLL set is deployed in standardized sections. Each section is marked with a high-flyer, usually equipped with a strobe light (and sometimes with GPS devices), to aid tracking of the gear during the soak, and to warn vessels of its presence.

PLL practices have been documented since the mid 1800's; the gear type was initially developed in Japanese fisheries to target Pacific bluefin tuna *Thunnus orientalis* and then expanded eastward to the United States and other nations in the early 20th century (Watson and Kerstetter 2006). Improvements in fishing technology have increased the efficiency of PLL gear over the decades. For example, the introduction of diesel-powered engines in the 1920s coupled with the introduction of freezer vessels in the 1950s allowed vessels to follow the target species' large-scale movements and remain on the fishing grounds longer (Watson and Kerstetter 2006; Ward and Hindmarsh 2007). The switch from iron hooks to high-carbon and stainless steel hooks in the 1950s and the introduction of a single-strand polyamide monofilament mainline in the 1970s (Watson and Kerstetter 2006) increased catchability by reducing the rates of fish loss (Ward and Hindmarsh 2007). The introduction of electronic devices, including GPS, radars, echo sounders, electric powered bandit reels, and computer- and satellite-aided data acquisition of current profiles, sea surface temperature, atmospheric patterns, and ocean bathymetry have also vastly increased PLL efficiency via enhanced navigation, communication, and ability to find target populations (Watson and Kerstetter 2006).

PLL fishermen are opportunistic and regularly modify gear configurations to target the most profitable species with each individual trip (SAFE 2014). Consequently, PLL gear is relatively non-selective and frequently interacts with bycatch species (i.e., non-target species), including protected sea turtles, marine mammals, and some seabird and shark species (SAFE 2014). Due to federal regulations, PLL fishermen are prohibited from landing these bycatch species and they are often discarded, whether alive or dead (HMS FMP 2006). Increased awareness of associated problems with high PLL bycatch (NOAA 2012) has enticed the development of gear technologies to reduce bycatch in PLL operations (Watson and Kerstetter 2006). Gear introductions include tori-lines and lineshooters to reduce seabird bycatch (Melvin 2000), circle hooks to reduce incidental catch of sea turtles, and "weak hooks" that allow much larger marine animals (e.g., porpoises, sharks, "giant" bluefin tuna) to bend the hook and thereby release themselves (Bigelow et al. 2012). Still further, altering operating characteristics including geographic area, month and time of fishing, fishing depth, and length of soak time can also increase the selectivity – and ultimately the sustainability – of PLL gear-based fisheries (Hoey and Moore 1999).

Figure 1. Diagram of modern (monofilament) pelagic longline gear. Not depicted to scale. Retrieved via: http://www.nmfs.noaa.gov



HMS Management and the WNA PLL Fishery

Management of the WNA PLL tuna fishery is relatively new compared to other natural resources. First enacted in 1976 as the Fishery Conservation and Management Act, the Magnuson-Stevens Fishery Conservation and Management Act (MSA) is the "primary law governing marine fisheries management in United States federal waters" (MSA 1996). At that time, the United States claimed ownership of marine territory from the coastline out to 200 nautical miles, thereby prohibiting foreign fleets from these waters (commonly referred to as the Exclusive Economic Zone, or EEZ). In 1990, after unsuccessful management by several coordinated U.S. regional fishery management councils, the Fishery Conservation Amendments gave the U.S. Secretary of Commerce authority to manage tunas in the U.S. EEZ (as well as other HMS in the Atlantic Ocean, Gulf of Mexico, and Caribbean Sea) under the MSA (HMS FMP 2006). The Secretary of Commerce, at that time, delegated authority of Atlantic HMS to the National Marine Fisheries Service (NMFS). The HMS Management Division, which manages and regulates all Atlantic HMS fisheries within the United States, was then created by NMFS (HMS MD 2014). The 1990 amendment also defined HMS to be marlin (*Tetrapturus* spp. and *Makaira* spp.), oceanic sharks, sailfishes (*Istiophorus* spp.), swordfish *Xiphias gladius*, and tuna species; including "BAYS" tunas (bigeye tuna *Thunnus obesus*, albacore tuna *Thunnus alalunga*, yellowfin tuna *Thunnus albacares*, and skipjack tuna *Katsuwonus pelamis*), and Atlantic bluefin tuna *Thunnus thynnus*.

The MSA was amended several times over the following years. Most notably, the MSA was amended with the Sustainable Fisheries Act (SFA) in 1996 requiring NMFS to create advisory panels (APs) to help develop fisheries management plans (FMPs) for Atlantic HMS (HMS MD 2014). The 1996 amendments focus on rebuilding over-fished fisheries, protecting essential fish habitat, and reducing bycatch. Per the SFA, the management of Atlantic HMS fisheries must also be consistent with other regulations such as the Marine Mammal Protection Act, the Endangered Species Act, the Migratory Bird Treaty Act, the National Environmental Policy Act, the Coastal Zone Management Act, and other Federal laws (HMS MD 2014).

However, fisheries management organizations acknowledged that new strategies had to be adopted in order to ensure the viability of U.S. marine fisheries. Thus, the

MSA was amended yet again in 2006 and re-named the Magnuson-Stevens Fishery Conservation and Management Reauthorization Act (MSRA). In essence, the MSRA continues to promote sustainable fisheries by: 1) mandating that regional fisheries management councils (of the U.S. Secretary of Commerce) end over-fishing; 2) stemming illegal, unregulated and unreported fishing (IUU fishing); 3) improving NOAA's fisheries science programs via enhanced fisheries monitoring protocols, and; 4) increase market-based management programs such as Limited Access Privilege Programs which, through catch-share allocations, promotes fishermen safety and economic viability of the fishery (MSRA 2008).

The management of U.S. Atlantic HMS fisheries is also governed by the Atlantic Tuna Convention Act (1975), which recognizes the need for international cooperation and mandates NMFS to implement domestically any management recommendations agreed upon by the International Commission for the Conservation of Atlantic Tunas (ICCAT) (HMS FMP 2014). Established in 1966, ICCAT is dedicated to the Atlantic-wide sustainable management of HMS. The organization also requires all member nations to collect scientifically sound catch and effort data, and to make that those data available to the Commission (ICCAT 2013). Each year, fisheries scientists from ICCAT members conduct stock assessments for most regulated Atlantic HMS in October, then the member nations meet in November to negotiate quotas and management recommendations based on these stock assessments. If these recommendations are adopted by ICCAT, then the United States must enforce them. Among the many international management bodies that could affect Atlantic HMS management [i.e., Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), the Food and Agriculture Organization of the United Nations (FAO) and International Plan of Action for the Conservation and Management of Sharks (IPOA-Sharks)], ICCAT is the most significant (HMS MD 2014).

Current management and regulations for Atlantic HMS can be found in the Code of Federal Regulations (title 50, chapter 6, parts 600-659). All management measures are detailed pertaining to each species defined by the HMS Management Division, and for each fish harvesting method that may effect the management of those species (e.g., demersal longlines, greenstick gear, swordfish buoy gear, pelagic longline gear, seines).

Aside from required vessel permits, fishery access restrictions, and gear identification, the most notable Atlantic HMS management measures include size limits, catch quotas, gear and deployment restrictions, commercial retention limits, time-area closures, and possession and sales restrictions (e-CFR 2013). In 1992, the Southeast Fisheries Science Center (SEFSC), one of six regional science centers operating under the direction of NMFS, launched the Pelagic Observer Program (POP). Although NMFS has used contracted fisheries observers to collect at-sea data since 1972, the POP was established as a measure of enforcement, record keeping, and most notably as a means for collecting scientifically sound catch and effort data for a variety of conservation and management issues specifically for pelagic (HMS) fisheries (POP 2014). Consequently, PLL *CPUE* derived from observer and commercial logbook data provide abundance indices that are imperative for developing stock assessments for Atlantic yellowfin tuna, bigeye tuna, swordfish, and other HMS. Although low, NMFS observer coverage has increased 10-fold since its inauguration. Observer coverage of the WNA PLL Fishery from the 2014 Stock Assessment and Fishery Evaluation (SAFE) Report for Atlantic HMS is presented in Table 1.

Table 1. U.S. Pelagic Observer Program federal fisheries observer coverage of the Atlantic pelagic longline fishery (1999-2013). NED- Northeast Distant Area; EXP- experimental.

Year	Number of Sets			Percentage of Total Number of Sets		
1999	420			3.8		
2000	464			4.2		
	Total	Non-EXP	EXP	Total	Non-NED	NED
2001[1]	584	390	186	5.4	3.7	100
2002[1]	856	353	503	8.9	3.9	100
2003[1]	1,088	552	536	11.5	6.2	100
	Total	Non-EXP	EXP	Total	Non-EXP	EXP
2004[2]	702	642	60	7.3	6.7	100
2005[2]	796	549	247	10.1	7.2	100
2006	568	-	-	7.5	-	-
2007	944	-	-	10.8	-	-
2008[3]	1,190	-	101	13.6	-	100
2009[3]	1,588	1,376	212	17.3	15	100
2010[3]	884	725	159	11	9.7	100
2011[3]	879	864	15	10.9	10.1	100
2012[4]	1,060	945	115	9.5	8.6	100
2013	1,528	1,474	54	14.4	14.1	100

[1] in 2001, 2002, and 2003, 100% observer coverage was required in the NED research experiment.

[2] In 2004 and 2005, there was 100 percent observer coverage for experimental sets (EXP).

[3] From 2008-2011, 100 percent observer coverage was required in experimental fishing in the FEC, Charleston Bump, and GOM, but these sets are not included in extrapolated bycatch estimates because they are not representative of normal fishing activities.

[4] In 2012, 100 percent observer coverage was required in a cooperative research program in the GOM to test the effectiveness of “weak hooks” on target species and bycatch rates, but these sets are not included in extrapolated bycatch estimates because they are not representative of normal fishing (SAFE 2014; p. 44).

Catch per unit effort: abundance indices and stock assessments

Fisheries management actions typically follow the results of some sort of stock assessment (Hilborn and Walters 1992). Fisheries stock assessments attempt to describe the past, present, and future status of a fish stock (Cooper 2006). Stock assessment models require information on both the fish population and the fishery including life history parameters (i.e., mortality, fecundity, and recruitment dynamics), relative abundance, and management regimes (Cooper 2006; Maunder and Punt 2004). Stock assessment models also attempt to predict how different management regimes (e.g., size limits, quotas, gear restrictions, time-area closures) will affect the stock. Although the assessment models for some species represent each directed fishery separately, many others worldwide do not. Stock assessment models (and subsequent management regimes) of commercially harvested HMS rely heavily on commercial logbooks (records reported directly by fishermen), landings records, and observer catch and effort data (Cooper 2006). PLL observer data from the NMFS POP and other sources are generally considered more reliable than commercial logbooks for Atlantic HMS because captain-entered logbooks are often anecdotal and because it is the most commonly used fishing gear for commercially-valued HMS species (Maunder et al. 2006; Lynch et al. 2012; Cooper 2006). Consequently, *CPUE* values derived from observer data are often the only reliable relative abundance indices available for commercially valued HMS stock assessments. However, it has been well recognized that raw *CPUE* data may not accurately reflect relative abundance due to lack of understanding of fishing effort distribution and HMS population dynamics (Harley et al. 2001; Wang et al. 2009; Walters 2003).

Catch per unit effort (*CPUE*) is a fishery statistic representing the number of fish landed per unit of fishing effort (Harley et al. 2001). The model for *CPUE* is as follows:

$$C_t = q\, N_t\, E_t \tag{1}$$

Where catch at time t, (C_t), is equal to the product of the amount of effort deployed (E_t), the abundance of the target stock (N_t), and the catchability coefficient (q), which is the proportion of the stock that is captured by one unit of effort. Rearranging equation *(1),*

$$C_t / E_t = CPUE_t = q\, N_t \qquad (2)$$

shows that *CPUE* is proportional to abundance assuming that *q* remains constant over time. This fundamental relationship allows fisheries scientists to use *CPUE* within stock assessment models as an index of relative abundance. Ideally, abundance indices should be based on fishery-independent data (i.e., standardized survey data); however, surveys for HMS are expensive and thus realistically impractical under current federal budget constraints (Maunder and Punt 2004; Ward and Hindmarsh 2007). Therefore, assessments of tunas, swordfish and other HMS stocks are based on fishery-dependent data (i.e., commercial logbook and observer program catch and effort data) that often violate the proportionality assumption (Cooper 2006).

From Equation *(2)*, we establish that *CPUE* is proportional to abundance assuming catchability *(q)* remains constant. This assumes that all fishes in a population have identical behavior, are evenly distributed in a given area, and that fleets have complete access to all parts of the area (Arreguín-Sánchez 1996). However, *q* is rarely constant and often changes spatially and temporally due to changes in fishing fleet dynamics (i.e., where and when fishing occurred) (Cooke and Beddington 1984; Hilborn and Walters 1992). Some of the prominent factors that effect catchability include changes in the efficiency of the fleet, changes in target species, environmental factors, the dynamics of fish populations, and fishing effort distribution (Arreguín-Sánchez 1996). However, the proportionality assumption is violated most often due to vessels targeting fish aggregations (Cooper 2006). Stable and consistent *CPUE* trends may be observed in the presence of a declining stock or, conversely *CPUE* may decline abruptly in the presence of stable stock abundance.

CPUE standardization, a method commonly used among fisheries scientists, attempts to remove the effects of variables not attributed to changes in abundance so that *q* can be assumed constant (Maunder and Punt 2004). The first standardization approaches from Beverton and Holt (1957) involved determining the relative fishing power of all vessels compared to a “standard vessel,” however defined for a particular fishery. Recently, generalized linear models (GLMs), which involve fitting statistical models to the catch and effort data instead of the “standard vessel” approach, have become the most common method for *CPUE* standardization (Maunder and Punt 2004). Standardizing *CPUE*, however, does not guarantee that the resulting abundance index is proportional to abundance. In fact, *CPUE* standardization often results in non-proportional abundance estimates (Figure 2) involving hyperstability (the most common non-proportionality, often resulting in overestimation of stock abundance) or hyperdepletion (leading to underestimation of stock abundance) (Harley et al. 2001). For example, in the case of northwest Atlantic cod fishery, increased effort and consistently high *CPUE*s during the 1970s and early 1980s led managers to believe that the stock was in good status (Walters and Martell 2004). However, the fishery collapsed in the late 1980s due to poor managerial regimes and subsequent over-fishing (Cudmore 2009). *CPUE*-based abundance indices are directly related to the spatial distribution of fishing effort and of the exploited fish resource. Therefore, *CPUE* can only be proportional to the part of the population vulnerable to the gear (Verdoit et al. 2003). For example, pelagic longline *CPUE* for yellowfin tuna mainly represents the abundance of large, deep-dwelling individuals in the population, while purse seine *CPUE* captures the abundance of smaller, surface-inhabiting fish (Maunder et al. 2006).

Figure 2. Relationship between *CPUE* and abundance based on differed values of the parameter β. The model of proportionality between *CPUE* and abundance *N* at time *t* is: $CPUE_t = q\ N_t^{\beta}$, where if $\beta = 1$ the model reduces to $CPUE_t = qN_t$ and if $\beta \neq 1$, then catchability changes with abundance (Harley et al. 2001, p. 1761). For the WNA PLL fishery, increased catch and effort at localized fishing locations usually leads to hyperstability interpretations, $\beta < 1$.

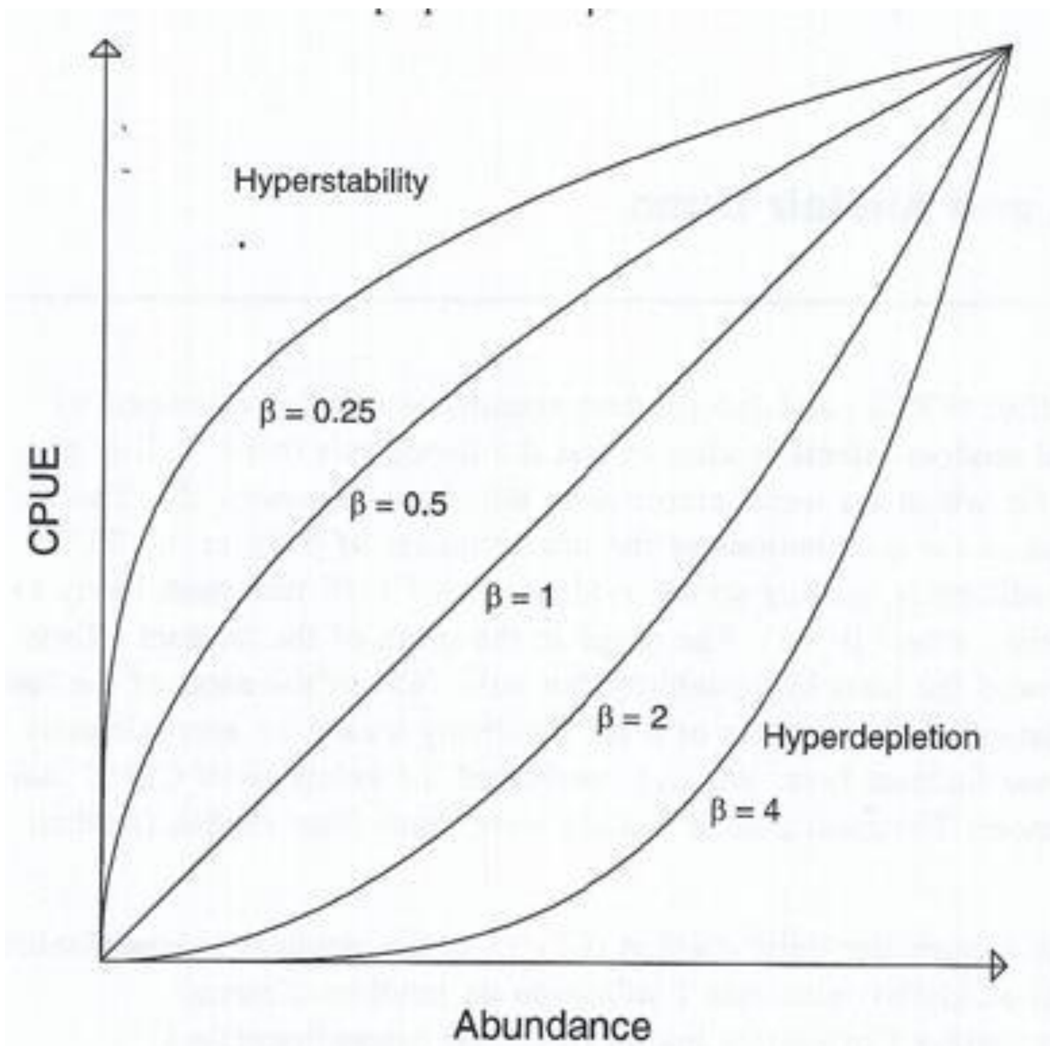
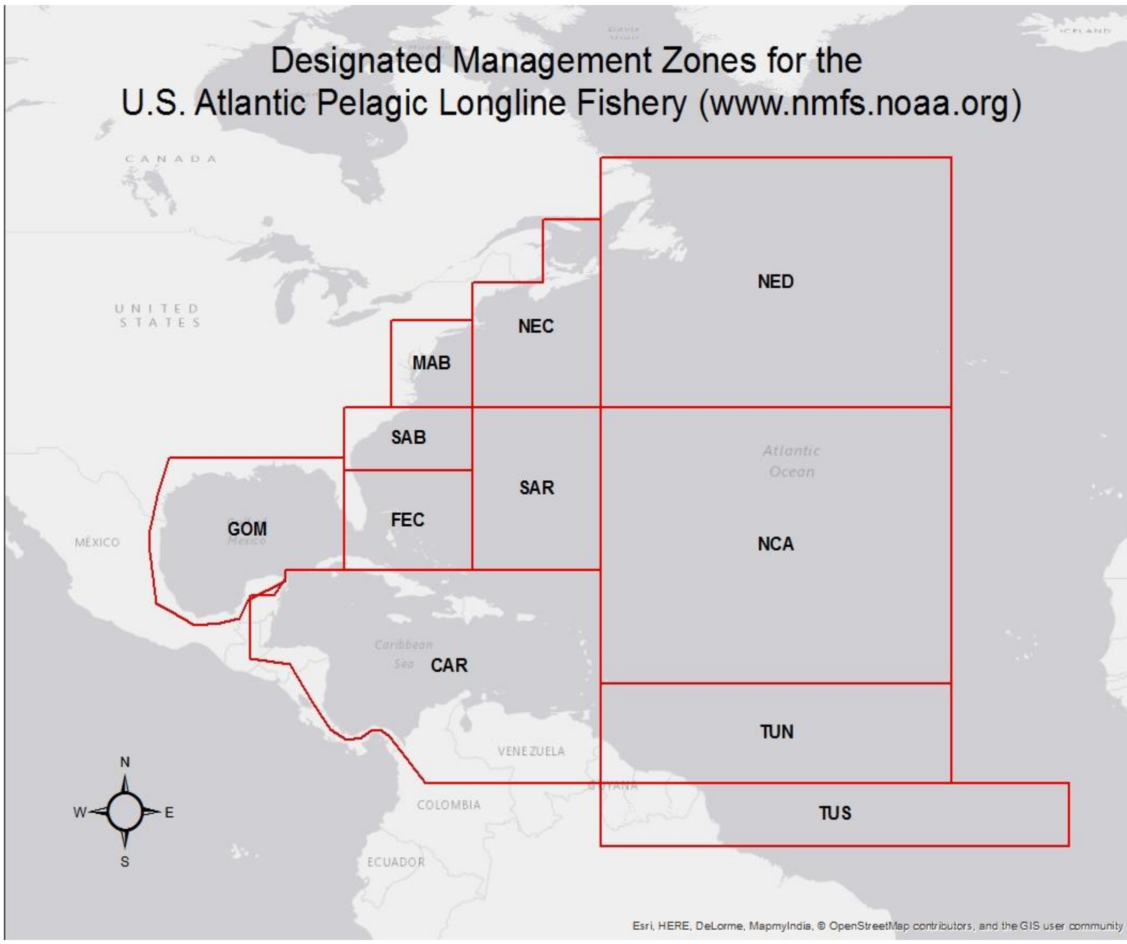


Figure 3. Designated Management Zones for the U.S. Atlantic pelagic longline fishery. GOM – Gulf of Mexico; CAR – Caribbean; FEC- Florida East Coast; SAB – South Atlantic Bight; MAB – Mid-Atlantic Bight; NEC – Northeast Coastal; SAR – Sargasso Sea; NED – Northeast Distant; NCA – North Central Atlantic; TUN – Tuna North; TUS – Tuna South



CPUE-based abundance indices also often assume that all non-fished areas within a geographical range behave the same. However, *CPUE* data are rarely proportional to abundance over an entire geographic region. Current and depth profiles, sea surface temperature, depth of thermoclines, and other physical and biological parameters create different sea conditions and influence biota differently within a large geographic area (Maunder et al. 2006; Harley et al. 2001; Maunder and Punt 2004). Hence, *CPUE* should only be used as an index of relative abundance at the spatial and temporal scales from which it was derived. Decades of fisherman's experience in a particular area generally reveal well-defined areas of increased target fish catch probability within the navigable limitations of the vessel. For the WNA PLL tuna fishery, effort is concentrated in a relatively small part of the target species geographic range. *CPUE*s are extrapolated from the fished areas to non-fished areas and are then applied to larger management areas (i.e. the designated management zones of the U.S. PLL fishery; Fig. 3) as an index of relative abundance. However, extrapolated abundance indices do not reflect true relative abundance in non-fished areas due to the frequently violated assumption that individuals are distributed proportionally throughout the species geographic range. Consequently, stock assessments conducted for HMS from extrapolated *CPUE*s tend to overestimate stock abundance (i.e., hyperstability per Harley et al. 2001)

<u>Spatial CPUE abundance indices</u>

The spatial distribution of fish and fishing effort is essential for understanding the proportionality between *CPUE* and stock abundance (Hilborn and Walters 1987). The distribution of HMS like tunas and swordfish are directly linked to environmental factors that are probably the main driver in population-wide transoceanic migrations or other movements (Maury et al. 2001). The relative movement of fisheries effort among areas of different fish aggregations introduces biases that may lead to hyperstability or hyperdepletion interpretations (Hilborn and Walters 1992; Carruthers et al. 2010). Figure 4 shows the changes in fishing effort and distribution for the US Atlantic tuna fleet (Carruthers et al. 2010). The majority of misunderstanding in fisheries modeling and management comes from dealing with these very different spatial and temporal scales (Moustakas et al. 2006). Although the need to incorporate spatial data in *CPUE*-based abundance indices has been well documented (Beverton and Holt 1957; Harley et al. 2001; Walters 2003; Maunder et al. 2006), abundance indices for Atlantic HMS are continually derived without accounting for fish and fishing effort distributions (Carruthers et al. 2010).

Several spatial analysis methods have been proposed utilizing catch and effort data from surveys, commercial logbooks, and onboard observers. Surveys are the preferred data source because the methods are often standardized and kept constant through time (Maunder and Punt 2004). A study by Can et al. (2004) was able to utilize survey data from the penaeid shrimp bottom-trawl fishery in Iskenderun Bay, Turkey, to create a spatially-based *CPUE* via the "swept area" method (i.e., the effective area covered by the trawl; commonly used for spatial *CPUE* based abundance indices of bottom-trawl fisheries). In Can et al. (2004), *CPUE* was defined as the catch in weight (*Cw*) divided by the swept area (*a*) for each species and for each haul:

$$CPUE = Cw / a \qquad (3)$$

Area-based methods like this are generally accepted as unbiased as long as the area is appropriately estimated and poorly sampled areas are weighted appropriately (Sullivan 1992). Can et al. (2004) define swept area (*a*) with the following equation:

$$a = D_i * h * X \qquad (4)$$

where D_i is the covered distance, *h* is the head-rope length, and *X* is the fraction of the head rope length that is equal to the width of the path swept by the trawl (Can et al. 2004). The distance covered (D_i) was calculated by the formula,

$$D_i = 60x \sqrt{(Lat_1 - Lat_2)^2 + \ (Lon_1 + Lon_2)^2 \ cos\ 0.5^2(Lat_1 + Lat_2)} \qquad (5)$$

where subscript 1 refers to latitude and longitude at the start of the haul and subscript 2 refers to latitude and longitude at the end of the haul (units were in nautical miles and then converted to kilometers). *CPUE*s were computed via equation (*3*) for each species and for each of two defined stratum. The results of this study are presented in Table 2. In a similar study by Pezzuto et al. (2008), swept area was used to assess seabob shrimp (*Xiphopenaeus kroyeri*) biomass for the artisinal shrimp trawl fishery in Southern Brazil utilizing observer data. Because observer data are fishery-dependent and there is strong variation between fishing effort distribution and fishing method between vessels, several critical assumptions had to be made by Pezzuto et al. (2008) regarding catchability and the sampling design. Inevitably, the variables used to define the effective swept-area are generally considered on a case-by-case basis for stock abundance estimates made using the swept-area method (Gunderson 1993).

For HMS like tunas and swordfish, data from commercial logbooks and onboard observers are considered the only reliable data available because pelagic fisheries surveys are generally too expensive to conduct due to the harvesting method and large-scale migratory behavior. Pelagic fisheries surveys are also considered biased because of the mismatch in survey locations and localized fish aggregations (ICCAT 2013). For the WNA PLL mixed tuna and swordfish fishery (as is the case for most pelagic fisheries), the fishery is divided into a number of regions and estimates for stock density are obtained from logbook and onboard observer catch and effort data for each region to account for spatial heterogeneity when deriving abundance indices (Campbell 2004). Assuming equal catchability across all individuals and regions, average regional catch rates weighted by size of each region gives a relatively unbiased estimate for total stock abundance. Using this approach, Langley (2004) found that spatially-based *CPUE*s from purse-seine logbooks in the west-central Pacific, although broadly similar to the nominal *CPUE*, did not show any overall trend over the entire time period. Also, the magnitude of variation in the nominal *CPUE* indices were far less compared to the spatially-based indices indicating that further investigation of fishery effort distribution is warranted. Similarly, a study by Jurado-Molina et al. (2011) developed a spatially adjusted *CPUE* for the albacore fishery in the South Pacific. Based on the results, the nominal *CPUE* was generally larger than the spatially adjusted *CPUE* and areas of high spatial *CPUE* emerged within the study region. However, the resulting spatial abundance indices from these studies are biased to favor regions with the most observations because equal weight is given to each observation as opposed to each region (Campbell 2004).

Figure 4. The spatio-temporal distribution of U.S. pelagic longline effort in the western North Atlantic. Panels represent effort in (a) 1990, (b) 1995, (c) 2000 and (d) 2005. Effort is reported in longline hooks. Bubbles represent relative effort scaled linearly and are comparable among panels (Carruthers et al. 2010).

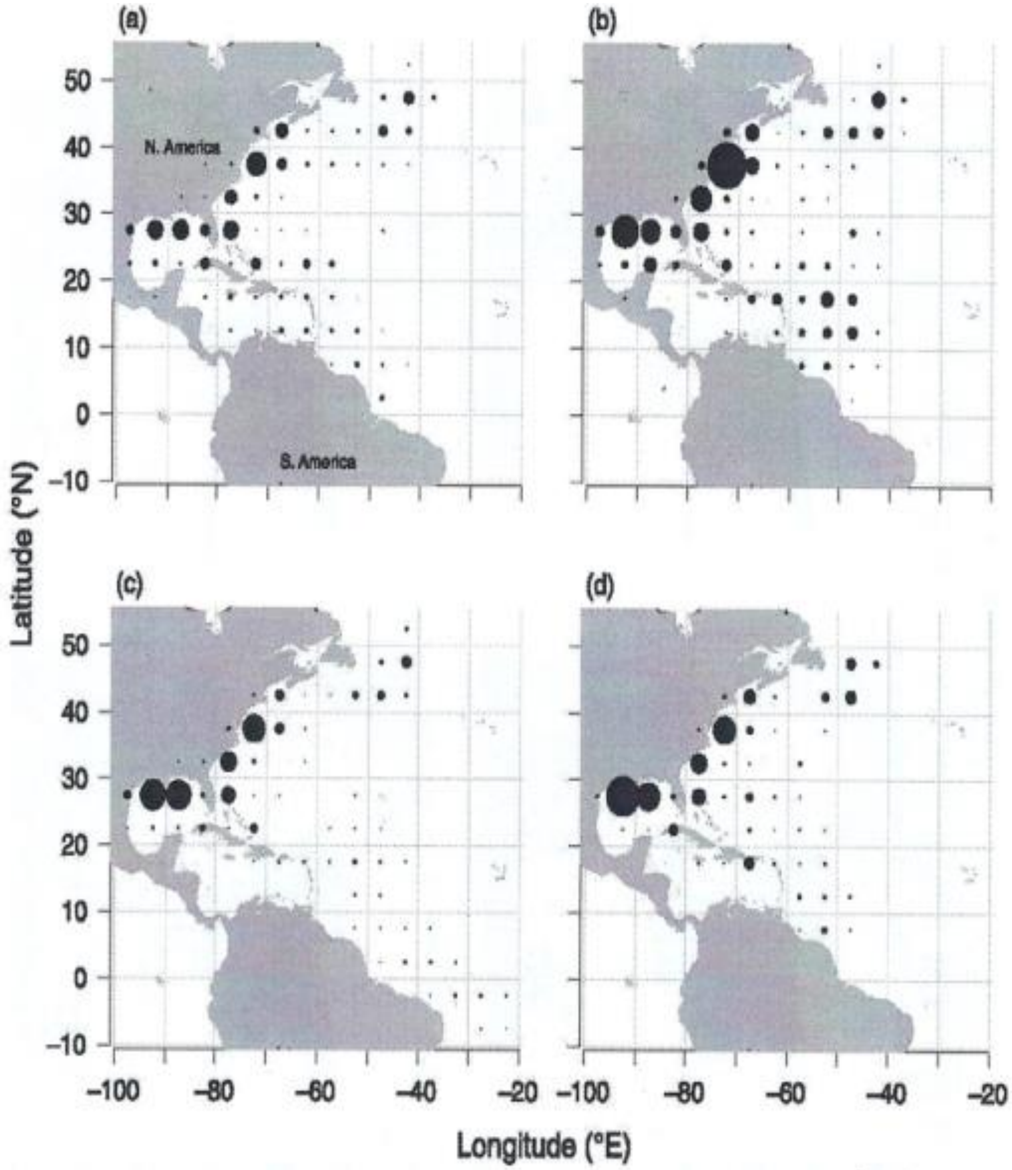


Table 2. Spatially-based *CPUE* utilizing survey data from the penaeid shrimp bottom-trawl fishery in Iskenderun Bay, Turkey. Mean *CPUE* (±SD) and Coefficient of Variation (CV) for strata and total area among the species for the bottom trawl shrimp fishery (Can et al. 2004).

Species	Stratum I	CV(%)	Stratum II	CV(%)	Total Area	CV(%)
P. semisulcatus	0.81 ± 0.51	63.1	12.57 ± 13.9	111.25	9.96 ± 13.29	132.8
M. stebbingi	76.38 ± 103.24	135.2	71.32 ± 60.9	85.45	73.43 ± 76.9	104.67
M. monoceros	–	–	47.84 ± 5.76	118.98	47.84 ± 5.80	118.98
M. japonicus	0.44 ± 0.20	45.74	1.59 ± 1.37	86.44	1.01 ± 1.10	108.78
M. kerathurus	0.47 ± 0.09	19.32	1.55 ± 1.43	92.33	1.25 ± 1.30	103.58

While most of the uncertainty in *CPUE*-based abundance indices is related to unequal spatial distributions of target fish and effort, biases can also enter due to inappropriate spatial scaling and missing observations (i.e., areas of fishery that are not fished) (Campbell 2004). Not only do regions within a fishery go un-fished, but the number and geographic location of regions fished also vary each year as a result of fishermen's awareness to the spatial distribution of target fish and increased ability to find and fish those areas. This spatial contraction can occur on any scale, and all variables should be accounted for when interpreting catch and effort data (Campbell 2004). Although GLMs are commonly used to deal with the inherent bias of nominal *CPUE* for spatial analysis, they are often refuted for their inapplicable assumptions (i.e., catchability and spatial contraction of the fishery overtime with respect to fish aggregations). As suggested by Campbell (2004), calculating a single reliable unbiased relative stock abundance index without spatial analysis is generally unattainable. Inevitably, the analysis of *CPUE*-based abundance indices should stem from the understanding and concepts of spatial distribution for both fishing effort and the stock in question. More specifically, *CPUE* should incorporate an area metric when used as an abundance index within stock assessment models.

Currently, HMS fisheries use point data for spatial referencing. In 2006, for example, NMFS implemented the Atlantic Pelagic Longline Take Reduction Plan (PLTRP). In summation, the goal of the PLTRP was "to reduce serious injuries and mortalities of marine mammals in the Atlantic pelagic longline fishery to insignificant levels." To accomplish this, the PLTRP team identified the distribution of marine mammal interactions within the PLL fishery (Figure 5). Essentially, each point represents the starting location of the set in which an interaction took place. Since PLL gear frequently exceeds 30 miles in length, the point does not accurately reflect the true location of the interaction. Additionally, the scale of spatial referencing for the WNA PLL fishery is extremely large. For example, Figure 6 is from the 2011 ICCAT yellowfin tuna stock assessment to show spatial distribution of yellowfin tuna catches. The size of the circles represent relative amount of observations that occurred within each 5 x 5 degree cell, which is a resolution on the scale of 100,000 km^2. This is what is required on an international level (ICCAT 2013), however for the U.S. PLL the spatial resolution can be refined to the scale of 10-100 km^2 utilizing GPS data that is currently recorded by all NMFS observers.

The objective of this thesis is to incorporate spatial PLL data to create a spatial *CPUE* ($^{S}CPUE$) for the U.S.-based PLL mixed tuna and swordfish fishery operating in the western North Atlantic (WNA). Theoretically, the widespread use of this new metric would increase the accuracy of abundance estimates and integrated stock assessments by eliminating the assumption that all non-fished areas of a population's geographic range have the same proportion of individuals as the fished areas, and instead provide an area-specific $^{S}CPUE$. Additionally, $^{S}CPUE$ may also aid fisheries managers when attempting to identify essential fish habitat (EFH), an increasing management concern due to legislative mandates (Magnuson-Stevens 1996). Jurado-Molina et al. (2011), among others, eloquently explain the exponential shift in fisheries management from single-species oriented regimes using quotas and restrictions to models that consider different types of fishing interactions affecting other species and the ecosystem, commonly referred to as "ecosystem-based fisheries management." When *CPUE* is analyzed within a spatial context, fisheries scientists are better able to describe particular areas of fishing grounds in terms of fish aggregations due to the behavior of large migratory pelagic fish species. In accordance with the same principle, spatial *CPUE* will identify non-target fish aggregations and aid in the global effort to reduce bycatch and increase the sustainability of marine fisheries. Spatial *CPUE* for the WNA PLL fishery will also help identify potential areas for protection for bycatch species, such as sea turtles, marine mammals, and sharks.

Figure 5. Marine mammal interactions from the 2006 Atlantic Pelagic Longline Take Reduction Plan (2014). Each non-grey point represents the starting location of the PLL set in which an observed marine mammal interaction occurred.

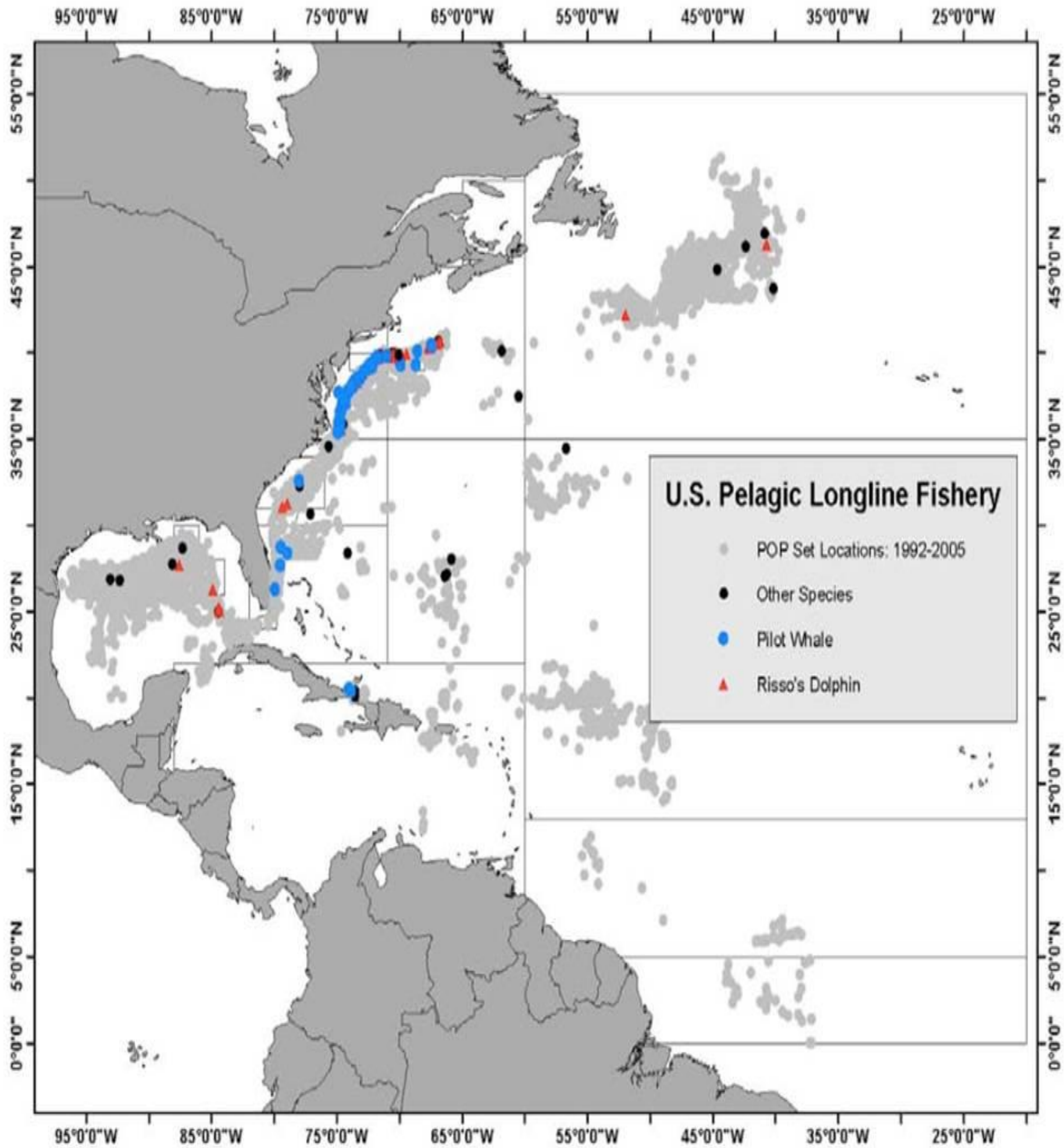
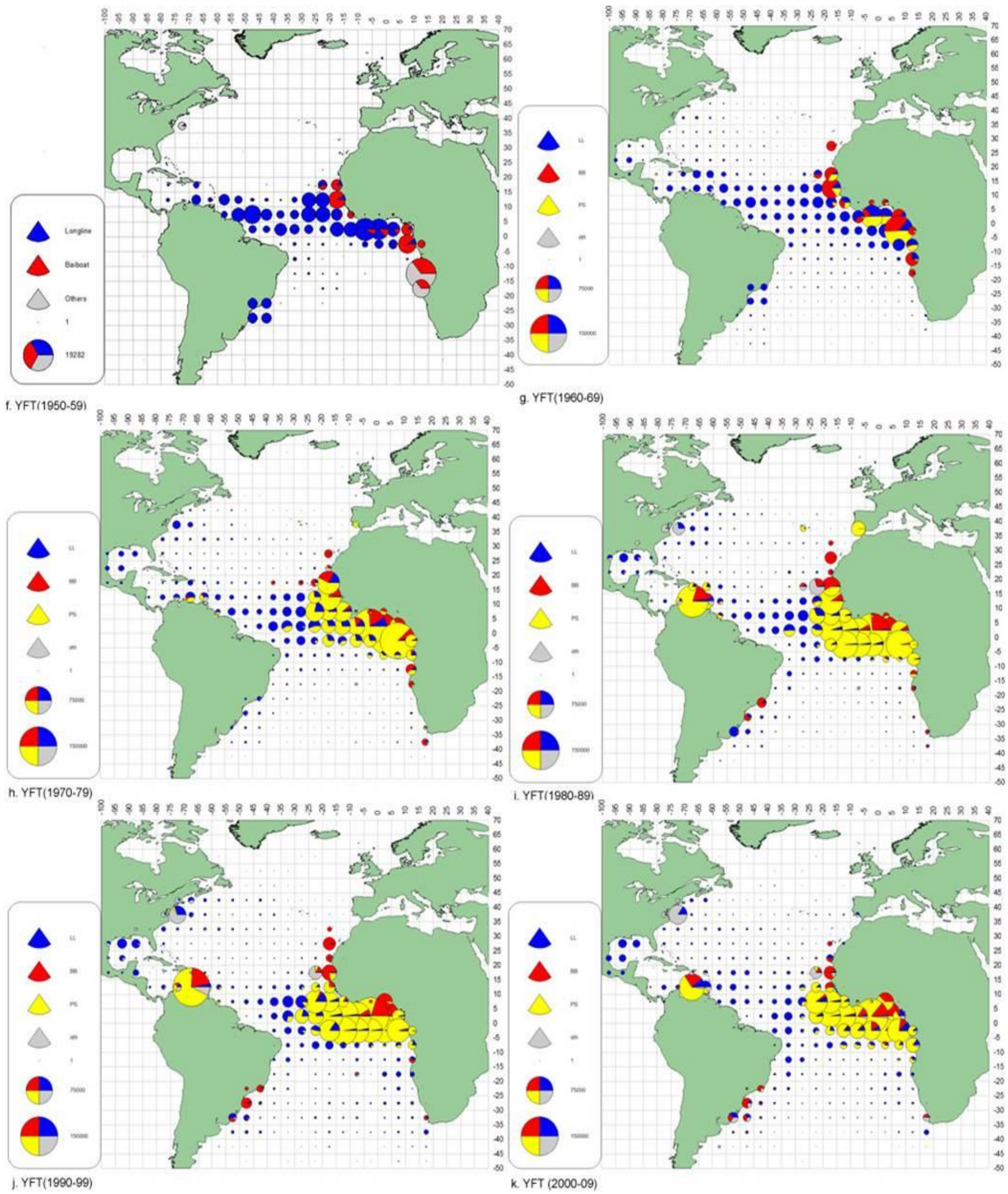


Figure 6. Spatial distribution of yellowfin tuna from the 2011 ICCAT yellowfin tuna stock assessment (2013). Size of circles represent relative amount of observations by major gears for each decade from 1950-2009.



Materials and Methods

Data collection

This study utilized seven years (2003-2006 and 2008-2010) of catch and effort data from the western North Atlantic U.S. PLL fleet targeting yellowfin tuna, swordfish and bigeye tuna. The WNA is defined herein as all waters off the U.S. east coast from 15-50º N (including the Caribbean Sea and Gulf of Mexico) extending east to the US EEZ (Exclusive Economic Zone). The 2003 and 2004 data were collected for the Kerstetter and Graves (2006) circle versus J-style hooks study. The 2005 and 2006 data were obtained directly from POP electronic record logs and are the only data sets utilized in this study lacking section-level GPS coordinates. The 2008-2010 data were collected by trained POP observers for NSU's time-area closure study in the FEC and SAB management zones funded by the NMFS.

Observers were professionally trained to collect reliable catch and effort data via standardized data sheets (Appendix I-IV). Each standardized data sheet was designed to specifically record a particular aspect of PLL fishing operations. For example, the Gear Log form was used to record data specific to the gear being used (e.g., type of mainline, gangions, hooks, buoys), while the Haul Log form was used to record geographic location information, time of fishing operations, water depth, speed, and heading, among others. The Animal Log form was used to record each individual animal that was observed interacting with the gear by species (i.e., all fish brought onboard, including animals that were removed from the gear and animals that were unintentionally released, whether alive or dead). Each data sheet included spaces for trip number, vessel name and number, date of haul, and haul number so that all four sheets correspond and can be traced to the same trip and set. Specific data that were utilized from each data sheet in this study are as follows:

(1) Trip summary logs: coverage area (corresponding to the management areas in Figure 3) and number of sets observed in each coverage area. These data provided a geographical visual of where each set occurred among the several management areas for the WNA U.S. PLL fishery. These data sheets were available for the 2008-2010 data sets only.

(2) Haul Log: target species, mainline length, number of hooks set, number of sections, and nautical coordinates at the beginning and end of both set and haul back. These data were used to characterize the set via target species and were the basis for calculating and developing a spatial *CPUE* metric. Section coordinates were also recorded for all sets from 2003-2004 and 2008-2010 data.

(3) Gear Log: trip number, vessel name and number and date landed. These data were used for data organization purposes.

(4) Animal Log: haul number, date of haul, the species code for each animal, and disposition of the target species (swordfish, yellowfin and bigeye tuna) and bluefin tuna were utilized. These data were used to create a spatial *CPUE* for each target species and bycatch species, including specific species of concern.

Spatial *CPUE* was calculated for 22 species and species groups of the approximately 80 different species that have historically been observed interacting with PLL gear in the WNA (POP 2014). Three of the selected species – swordfish, yellowfin and bigeye tuna – are primary target species of the fishery, while the remaining 19 species and species groups were specifically selected for this study because NMFS has identified them as particular species of concern with specific objectives highlighted in the agency's HMS Fishery Management Plan (HMS FMP 2006). Species were also selected due to the increasing pressure for protection from regional and federal mandates, most notably for the highly-prized and -valued western Atlantic bluefin tuna (SAFE 2014). A full list of species codes and species group codes used in this study are listed in Table 3. Animals were recorded on temporary animal tally logs to expedite data entry (Appendix V). Species that were observed on the Animal Logs, but were not listed for the purpose of this study, were omitted from the data and were therefore not counted toward the total animal tally.

Table 3. List of species and species group used in analysis. Species codes are consistent with NMFS Pelagic Observer Program. BLK and SKJ were lumped into TUN for the purpose of this study.

Common Name	**Latin Name**	**Code**
swordfish	*Xiphius gladius*	SWO
yellowfin tuna	*Thunnus albacares*	YFT
bigeye tuna	*Thunnus obesus*	BET
bluefin tuna	*Thunnus thynnus*	BFT
blackfin tuna	*Thunnus atlanticus*	BLK
albacore tuna	*Thunnus alalunga*	TUN
skipjack tuna	*Katsuwonus pelamis*	SKJ
sea turtles	Cheloniodea	TTX
marine mammals	Mammalia	MAM
billfish	Istiophoridae	BIL
skates and rays	Batoidea	SRX
pelagic stingray	*Pteroplatytrygon violacea*	PEL
sharks	Selachimorpha	SHX
requiem sharks	*Carcharhinidae spp.*	SRQ
hammerhead sharks	*Sphyrna spp.*	XHH
shortfin mako	*Isurus oxyrinchus*	SMA
tiger shark	*Galieocerdo cuvier*	TIG
oceanic whitetip	*Carcharhinus longimanus*	OCS
blue shark	*Prionace glauca*	BSH
escolar	*Lepidocybium flavobrunneum*	GEM
oilfish	*Revettus pretiosus*	OIL
barracuda	*Sphyraena spp.*	BAR
Dolphinfish	*Coryphaena spp.*	DOL
wahoo	*Acanthocybium solandri*	WAH

<u>*Deriving Spatial CPUE*</u>

PLL *CPUE*s that are used to derive abundance indices for species in the NWA tuna fishery are currently defined as:

$$CPUE_{spp} = N_{spp} / 1000\ hooks \tag{6}$$

where N_{spp} is the number of fish for a species. If, for example, five yellowfin tuna (YFT) were landed with 500 hooks deployed, then $CPUE_{YFT}$ = 10. Dividing equation *(6)* by the total area fished by the gear during the soak gives the equation:

$$^{S}CPUE_{spp} = N_{spp} / 1000\ hooks / A_n \tag{7}$$

where A_n is the total area in km^2 for set *n*. This equation, *(7)*, incorporates a spatial metric derived directly from the observed PLL set and defines the resulting spatial *CPUE* metric ($^{S}CPUE$) for the WNA PLL mixed tuna and swordfish fishery. As mentioned previously, $^{S}CPUE$ was calculated for the target species of the fishery, as well as 19 other species or species groups of particular concern, for each observed PLL set, and section when applicable, within the 2003-2006 and 2008-2010 data sets.

<u>*Statistical Analysis*</u>

Non-spatial Statistical Analysis and Perceived-Area-Fished (PAF)

Standard *CPUE* (i.e., number of fish per 1000 hooks; the current metric for catch per unit effort) was calculated for retained SWO for each full set (A_f) from the study data set and compared to $^{S}CPUE$ derived from the same data set to identify any statistical difference between the values. Since the metrics for these values do not allow for direct comparison (e.g., t-tests or ANOVAs), the values were compared via skewness and kurtosis distribution analysis. For calculating the total area fished by the gear during the soak, the nautical coordinates (i.e., latitude and longitude) recorded by the onboard observer via handheld GPS units at the start and end of each set and haul were converted from degrees, minutes and seconds to decimal degrees (DD). Microsoft Excel (MS Excel

2010) served as the data organization platform and the execution of non-spatial statistical analysis for this study.

ESRI ArcMap 10.2 was the GIS platform used to visualize each longline set in two-dimensions. Data was imported into ArcMap using a UTM projected coordinate system. Polygon shapefiles (.SHP) were created by connecting the four coordinates from the start and end of the set and haul back for both full set and section-level data, and for all seven years. Each polygon received an individual identification number. The resulting polygons represent the “perceived-area-fished” (PAF), or the total area that the gear occupied as it drifted with the surface currents during the soak. The PAF in terms of square kilometers was calculated using the calculate geometry tool in the attributes table. The PAF provided the spatial component for ${}^{S}CPUE$. Sections with observed part-offs (i.e., where the mainline was severed intentionally by the fishermen or unintentionally due to animal interaction during the haul) in excess of 30 minutes were omitted from analysis because this scenario frequently creates uncharacteristic drift patterns. Finally, the attributes (i.e., catch and effort data and ${}^{S}CPUE$'s for all 22 species and species groups) were joined to each full set and section-level polygon using the individual identification number.

This study examined three methods of calculating PAF. The first method (A_f) using four coordinates from the start and end of the set and haulback of the full set. The second method (A_s) using four coordinates for each section of longline gear. And the third method (A_{fs}) which uses the area of the full set via the sum of the sections that create that same set (Figure 7). A_f and A_{fs} were compared via a two-tailed T-test (and were similarly compared to A_s) to test if there was any statistical difference in PAF. Additionally, skewness and kurtosis distribution analysis were conducted to provide further insight about the difference between PAF values.

${}^{S}CPUE$*'s* were calculated using each PAF calculation. Since most full sets had more than one corresponding section-level ${}^{S}CPUE$ (i.e., ${}^{S}CPUE$ values derived using the A_s PAF calculation), those values were averaged within sets creating a single section-level ${}^{S}CPUE$ (A_{s_i}) (refer to Figure 7) to allow for direct comparison of section-level ${}^{S}CPUE$ to both full set-level ${}^{S}CPUE$ values (i.e., ${}^{S}CPUE$ values derived using A_f and A_{fs} PAF calculations) via one-way ANOVA. Pending the results of the ANOVA, ${}^{S}CPUE$

values were then compared via two-tailed T-tests to identify statistical differences between each of the three values (i.e., A_f vs A_{s_1} vs A_{fs}). $^{S}CPUE$ for retained SWO from the 2009 subset was used for this analysis because it had the largest sample size with complete section-level data (N = 66).

Hot Spot Analysis

Full set (A_f) polygon .SHP files from each year (2003-2006 and 2008-2010) were merged into a single .SHP file. Using the fishnet tool, a grid was created over the entire study area. Each cell of the grid measured 0.1 x 0.1 DD (approximately 5 miles latitude x 6 miles longitude or 8 x 9.6 km). With the spatial join tool, the average of the attributes falling within each cell was calculated. All of the cells in which no fishing occurred were removed prior to analysis. The optimized "hot spot" analysis tool was used to identify statistically significant spatial clusters of high values (hot spots) and low values (cold spots) via the Getis-Ord Gi* statistic (ArcGIS Resources 2014). Instead of manually selecting the appropriate scale, multiple testing, and spatial dependence criteria, the optimized hot spot analysis tool interrogates your data and automatically determines settings that will produce optimal hot spot analysis results. Due to the dynamic nature of HMS, a 2 km buffer was created around each statistically significant hot spot (Figure 8A) in order to accurately describe the hot spot in terms of area and location. New polygons were created via a modified minimum convex polygon method (Figure 8B) using the perimeter of the buffer as a guide. The area of the new polygon (i.e., the statistically significant hot spot) was calculated via the same method of PAF.

The hot spot analysis method described above was applied to fishing effort distribution, $^{S}CPUE$ and corresponding $CPUE$. Of the 22 species used in the analysis, two were chosen as example species for results and discussion purposes: 1) retained SWO because majority of PLL sets directly targeted SWO, and; 2) istiophorid species (billfishes, abbreviated as BIL) because they are increasingly referenced by NMFS as particular species of concern for management (SAFE 2014). To qualitatively explore temporal changes in hot-spot location, the described methods were applied to the 2008-2010 data sets which were all observed in accordance with a NOAA-funded time-area closure study in the FEC and SAB statistical management zones conducted by the NSU Fisheries Research Laboratory (Kerstetter 2011).

Figure 7. Three different methods for calculating perceived area fished (PAF). Inset map: longline set #376 from 2008. The green polygon represents A_f and was created using the four coordinates from the start and end of the set and the haulback. The yellow polygons represent A_s and were created using four coordinates from the start and end of the set and haulback for each section buy. A_{fs} is the sum of all the yellow polygons creating the same set, and $A_{s'}$ is the average of all the yellow polygons from the same set. In this example A_f = 567.8 km^2 and A_{fs} = 709.2 km^2, a 25% increase in PAF. $A_{s'}$ is the average of $^{S}CPUE$ via the A_s method from a set to allow for direct comparison with $^{S}CPUEs$ for the full set (A_f and A_{fs}).

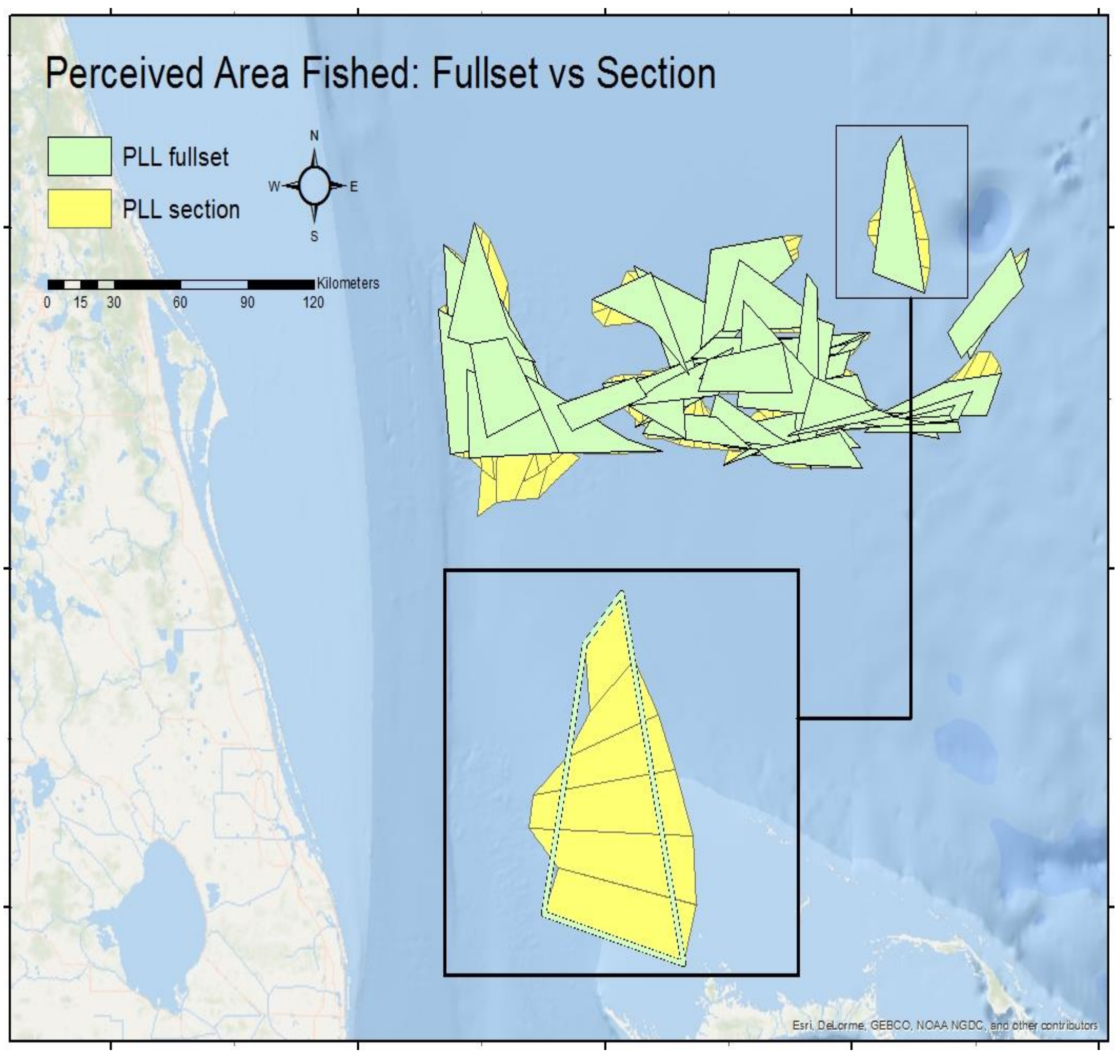


Figure 8A. ArcGIS screen shoot: 2 km buffer around cells with Gi Bin scores ≥ 2.

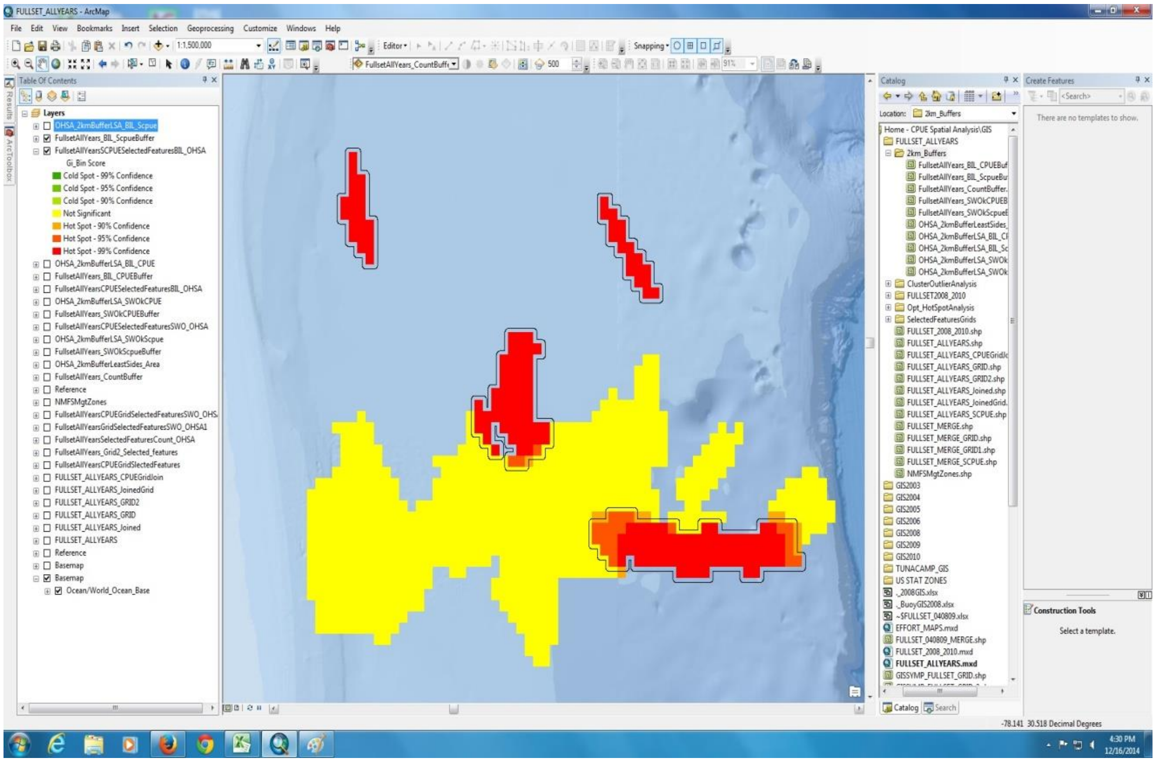
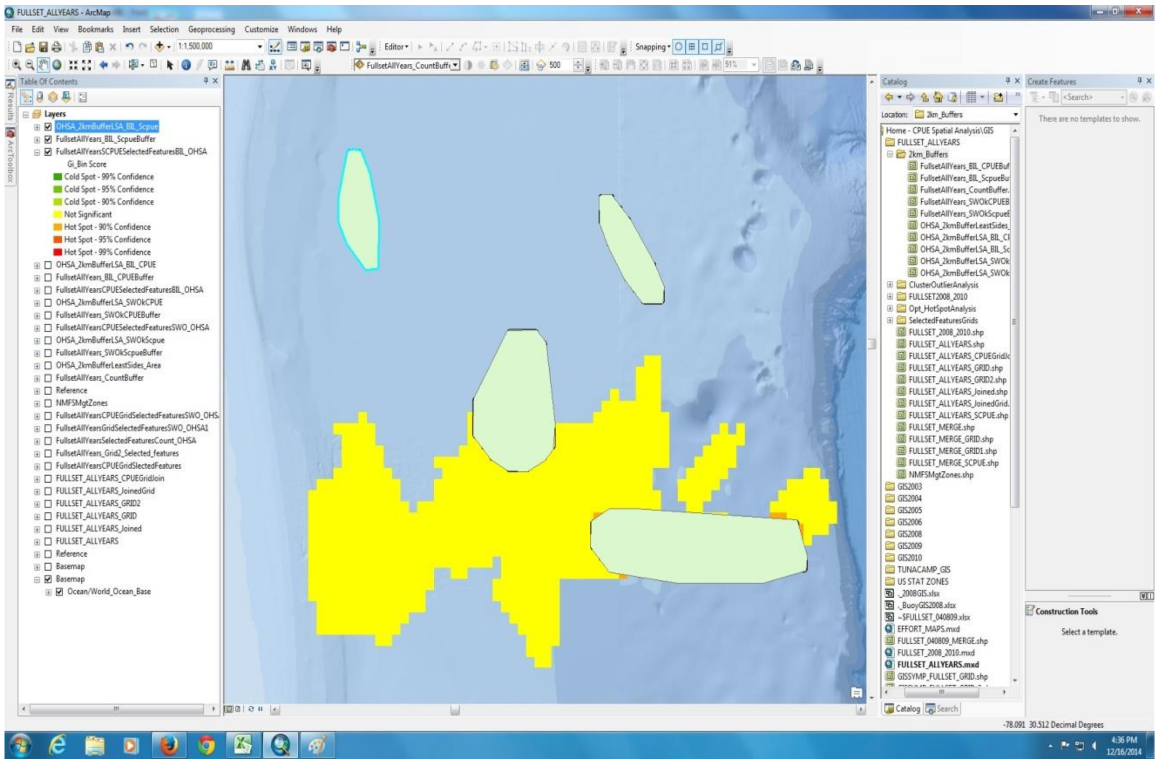


Figure 8B. ArcGIS Screen shot: minimum convex polygons created around buffer.



Results

Non-spatial Statistics

Data from a total of 534 PLL sets were used in this study. Approximately 40% (n=215) of those sets had complete section-level data, with less than 30 minutes of recovery time due to part-offs, equating to 1,403 PLL sections. These sets fished approximately 402,711 km^2 within five of 11 designated management zones for the U.S. Atlantic PLL fishery (NEC, MAB, SAB, FEC, and GOM; Figure 9A). In total, there were 15,686 animal interactions relevant to this study. The primary target species for PLL sets by year are presented in Table 4. 64% of PLL sets directly targeted swordfish, and 23% targeted both swordfish and tuna species (i.e., yellowfin and bigeye tuna; Figure 10). The number of animal interactions by species or species group code is presented in Table 5. A complete analysis of fishing effort by year is included in Table 6.

Results of a two-tailed T-test indicate that there was no significant difference between full set PAF calculations (A_f vs A_{fs}, $p = 0.268$; Table 7). A_s was also compared to A_f via a two-tailed T-test ($p = 3.96 \times 10^{-60}$), although the significant difference between these values was apparent prior to testing, since A_s is two to three orders of magnitude smaller than both full set PAF calculations. Supplemental distribution analysis results indicate that while A_f and A_{fs} are similar in distribution (K = 1.44 and 0.58; and S = 1.38 and 1.19, respectively), the distribution of A_s has strikingly higher skewness (S = 2.32) and kurtosis (K = 9.32) than both A_f and A_{fs} distributions (Table 8).

The distribution analysis results of *CPUE* and ${}^{S}CPUE$ values indicated that both were positively skewed (S = 2.03 and 9.32, respectively; Figure 11A and 11B); however, the kurtosis value for ${}^{S}CPUE$ was 20 times greater compared to that of the standard *CPUE* (K = 104.7 and 5.12, respectively). The range for 95% of ${}^{S}CPUE$ values is three orders of magnitude smaller than that for *CPUE* ($R_{95\%}$ = 0.17 and 47.9, respectively), indicating much less variability in ${}^{S}CPUE$ values compared to *CPUE*.

Results of a one-way ANOVA (Table 9) indicate that there was a significant difference in the means of the three ${}^{S}CPUE$ values for the 2009 subset ($F = 11.96 > F_{crit}$, $p < 0.05$). Further analysis (Table 10) indicates that ${}^{S}CPUE$ values derived from A_f and

A_{fs} PAF calculations did not differ significantly from each other ($p > 0.05$), while $^{S}CPUE$ values derived from $A_{s\prime}$ differed significantly from both A_f and A_{fs} ($p < 0.001$).

Figure 9A. 2003-2006 and 2008-2010 observed pelagic longline ${}^{S}CPUE$ study sets. Refer to Figure 3 for management zones.

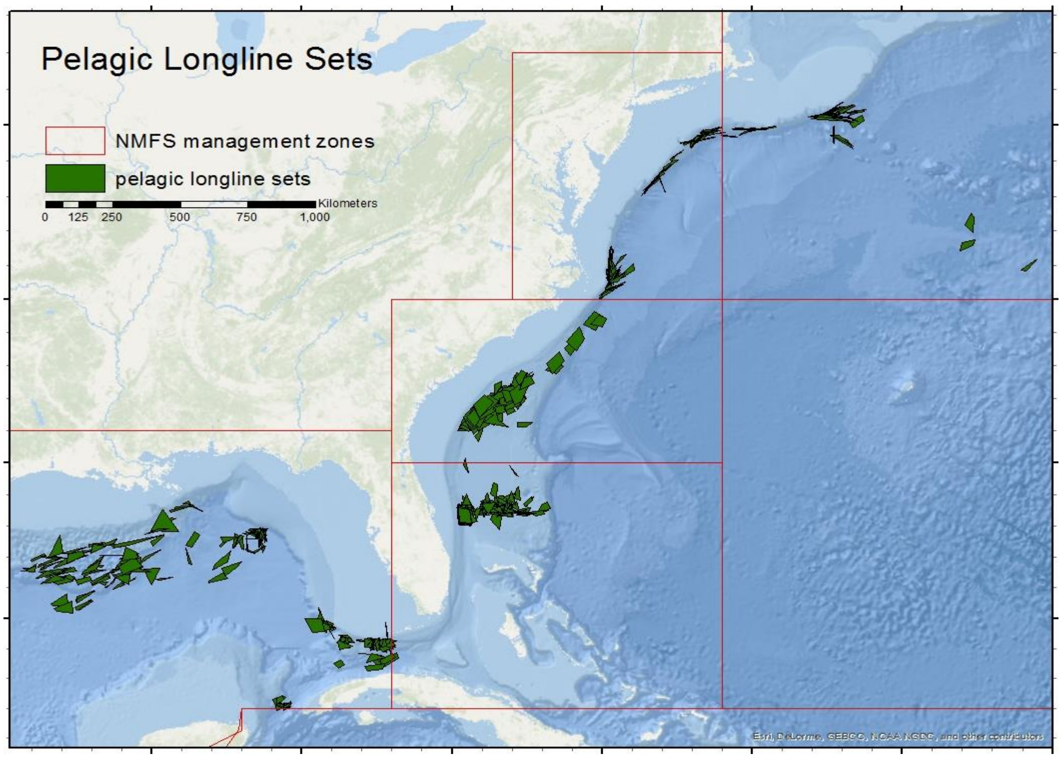


Figure 9B. 2008-2010 observed pelagic longline $^{S}CPUE$ study sets.

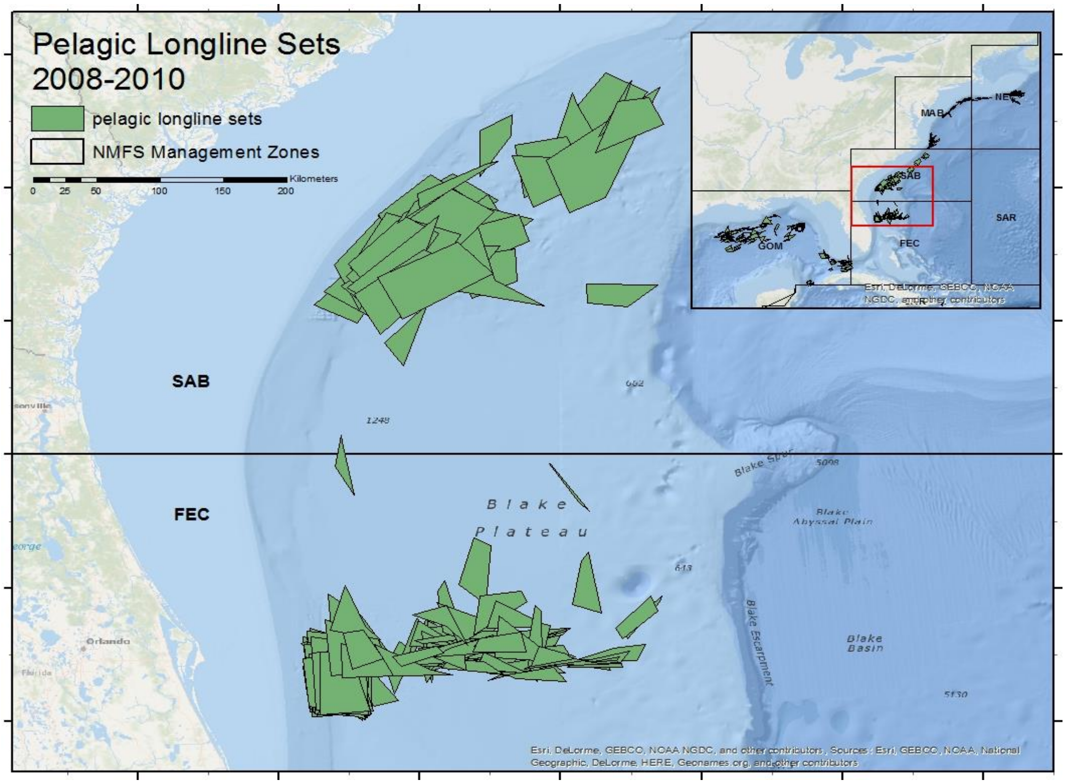


Table 4. Target species for observed longline sets by year (N = 534). Refer to Table 3 for species codes.

Year	SWO	MIX	YFT	TUN	DOL
2003	34	0	0	0	0
2004	38	0	0	0	0
2005	65	40	28	17	0
2006	57	73	9	11	0
2008	44	9	0	0	0
2009	68	3	0	0	4
2010	34	0	0	0	0
TOTAL	340	125	37	28	4
% Targeted	64%	23%	7%	5%	1%

Figure 10. Percent Species Targeted.

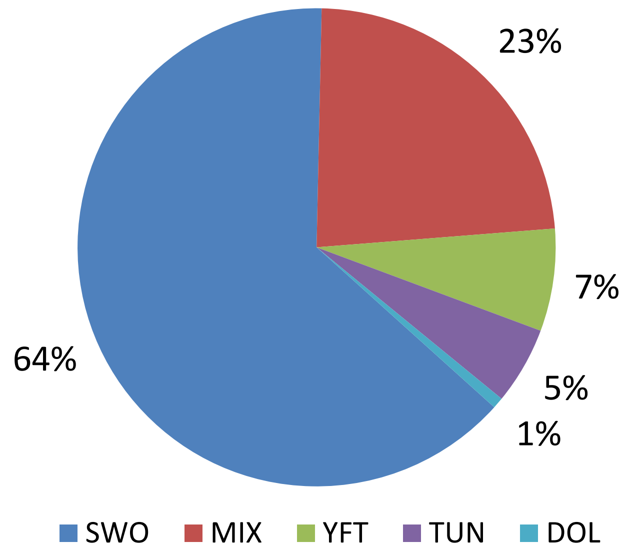


Table 5. Total animals by species and by year. Refer to Table 3 for species codes.

YEAR	[1]2003	2004	[2]2005	2006	[3]2008	2009	2010	TOTAL
SWO	289	551	1556	1,170	394	1,067	366	5,393
YFT	188	1	838	1,403	49	25	35	2,539
BET	49	3	224	206	204	71	53	810
BFT	0	0	21	89	0	0	1	111
TUN	42	10	211	275	38	18	30	624
TTX	12	3	11	23	2	1	0	52
MAM	4	0	8	12	0	0	0	24
BIL	30	17	130	127	73	137	65	579
SRX	8	0	19	47	20	2	2	98
PEL	267	1	157	208	15	25	12	685
SHX	128	34	63	87	19	38	13	382
SRQ	30	67	337	130	116	298	129	1,107
XHH	5	1	29	16	1	20	5	77
SMA	3	1	46	92	3	10	4	159
TIG	9	4	36	66	35	55	40	245
OCS	0	3	3	6	4	14	9	39
BSH	115	0	106	198	8	18	11	456
GEM	0	52	223	59	25	17	8	384
OIL	0	9	32	33	32	26	9	141
BAR	0	12	1	6	11	32	42	104
DOL	139	15	336	237	58	762	35	1,582
WAH	1	3	39	39	3	8	2	95
TOTAL	1,319	787	4,426	4,529	1,110	2,644	871	15,686

[1] Observer data from BIL sat-tag study predominantly conducted in the MAB and GOM management zones

[2] Observer data from NMFS online database

[3] Observer data from the NMFS Time-Area Closure study for East Florida Coast closed area.

Table 6. Number of hooks, area fished, and number of sets used for each perceived area fished method by year. A_s – area using four coordinates from the start and end of the set and haul for each section; A_f – area using four coordinates from start and end of the set and haul for the full set; A_{fs} – area calculated via the sum of the sections that make that same full set. Area fished is presented in km^2 and represents the sum of all the full sets via the A_f perceived area fished method which had the largest sample size (N=534)

YEAR	Full set (A_f)	Full set (A_{fs})	Sections (A_s)	Hooks	Area Fished (A_f)
2003	34	33	219	22,997	3,063
2004	38	38	183	16,211	15,865
2005	150	–	–	106,547	133,136
2006	150	–	–	101,573	87,047
2008	53	53	343	24,520	25,011
2009	75	66	468	35,710	97,938
2010	34	25	190	16,730	40,650
TOTAL	534	215	1,403	324,288	402,710

Table 7. Perceived Area Fished (PAF) statistical analysis. A_s – area using four coordinates from the start and end of the set and haul for each section; A_f – area using four coordinates from start and end of the set and haul for the full set; A_{fs} – area calculated via the sum of the sections that make that same full set. Results of a two-tailed T-test (p < 0.05) indicates a statistically significant difference between the PAF calculations. Only one full set PAF value was tested against A_s since the p-value from A_f and A_{fs} is > 0.05.

	A_f	A_{fs}	A_s
Mean	745.4	832.9	128.7
SD	761.1	869.2	150.2
SEM	51.9	59.3	4.0
VAR	576555.2	752067.4	22536.9
p-value (A_f vs A_{fs})		0.267855	
p-value (A_f vs A_s)		3.96×10^{-60}	

Table 8. Perceived area fished (PAF) distribution analysis results. A_s – area using four coordinates from the start and end of the set and haul for each section; A_f – area using four coordinates from start and end of the set and haul for the full set; A_{fs} – area calculated via the sum of the sections that make that same full set.

Area Type (km²)	A_s	A_f	A_{fs}
Maximum	1,410.9	4,475.6	4,285.9
Minimum	0.10	5.44	20.50
Mean	128.7	754.1	832.9
Kurtosis	9.33	1.44	0.58
Skewness	2.32	1.38	1.19
Sample size (N)	1404	534	215

Figure 11A. Histogram of full set (A_f) *CPUE* values. S – skewness; K – kurtosis; $R_{95\%}$ – range of 95% of values (first 5 bins); N = 534. Bin values reflect 10% increments of the maximum *CPUE* value (max *CPUE* = 95.83 retained SWO/1000 hooks; bin range = 9.58).

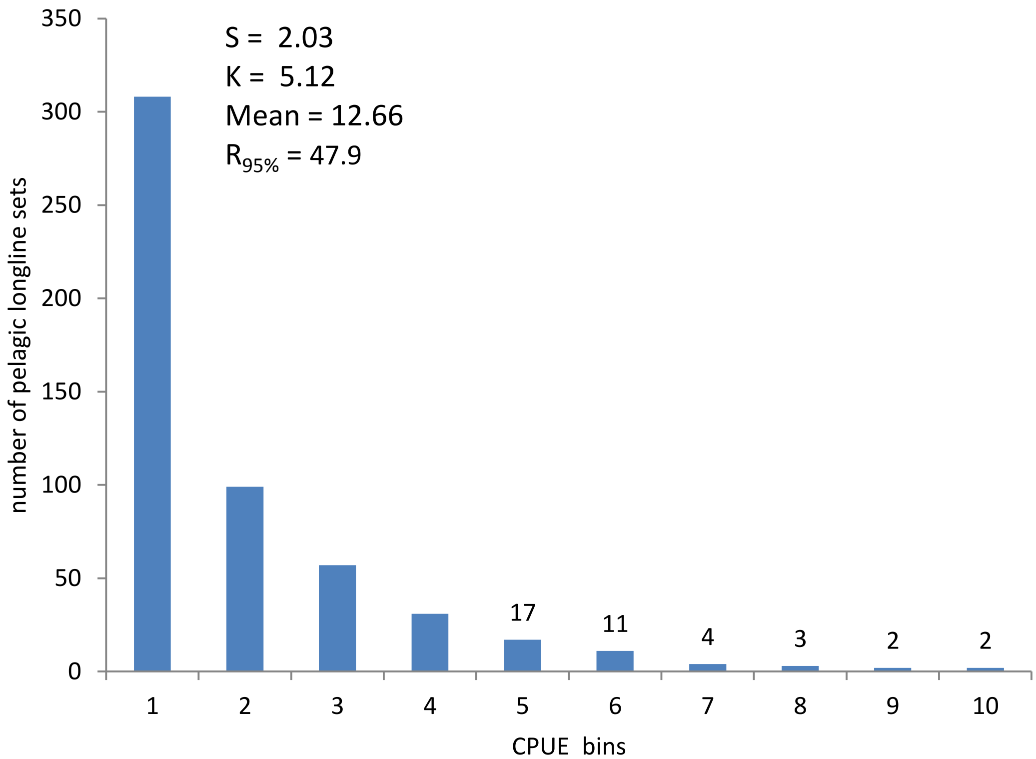


Figure 11B. Histogram of full set (A_f) ${}^{S}CPUE$ values. S – skewness; K – kurtosis; $R_{95\%}$ – range of 95% of values (first bin); N= 534. Bin values reflect 10% increments of the maximum ${}^{S}CPUE$ value (max ${}^{S}CPUE$ = 1.74 retained SWO/1000hooks/km^2; bin range = 0.17).

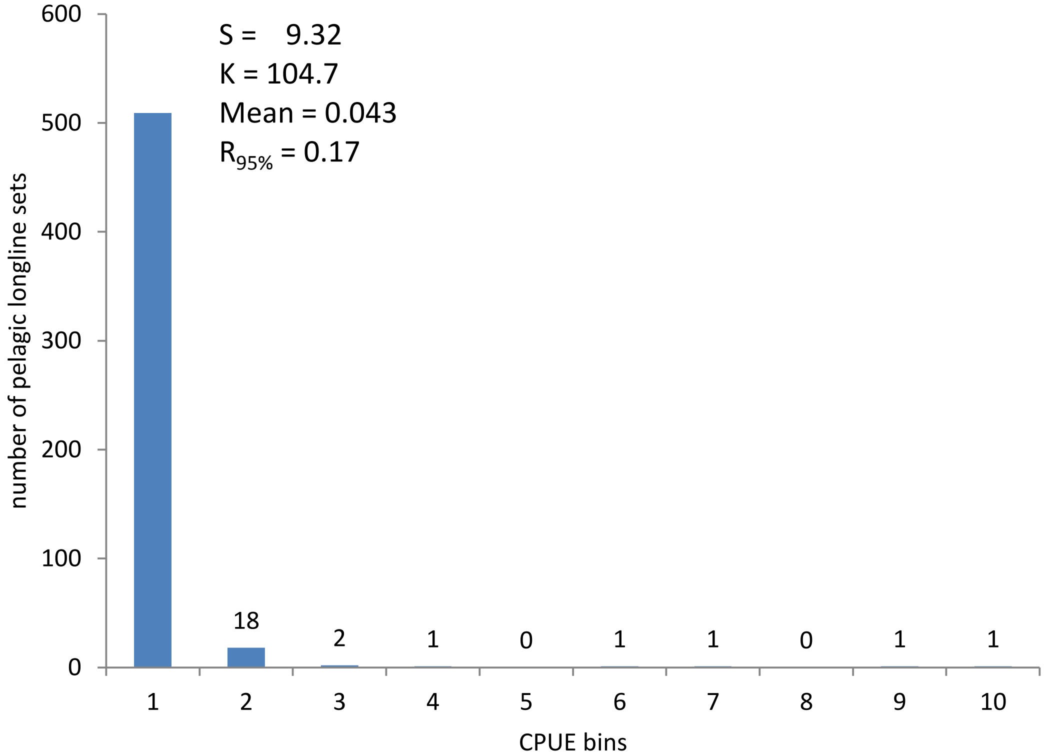


Table 9. Summary and results of one-way ANOVA for three methods of calculating $^{S}CPUE$ for retained SWO via different PAF calculations for the 2009 subset. A_s – area using four coordinates from the start and end of the set and haul for each section; A_f – area using four coordinates from start and end of the set and haul for the full set; A_{fs} – area calculated via the sum of the sections that make that same full set; A_{s1} is the average of A_s for the full set. F > Fcrit and *p-value* < 0.05, therefore a statistically significant difference exists between the three values.

^{S}CPUE methods	**Count**	**Sum**	**Average**	**Variance**		
A_f	66	–	0.0305	0.0018		
A_{fs}	66	–	0.0300	0.0022		
A_{s1}	66	–	0.3334	0.5035		
Source of Variation	**SS**	**df**	**MS**	**F**	***P-value***	**F crit**
Between Groups	4.04	2	2.02	11.96	1.26×10^{-5}	3.04
Within Groups	32.98	195	0.17			
Total	37.03	197				

Table 10. Results of two-tailed T-test for three methods of calculating $^{S}CPUE$ for retained SWO via different PAF calculations for the 2009 subset. A_s – area using four coordinates from the start and end of the set and haul for each section; A_f – area using four coordinates from start and end of the set and haul for the full set; A_{fs} – area calculated via the sum of the sections that make that same full set; A_{s1} is the average of A_s for the full set. A_{s1} is statistically different from both A_f and A_{fs} (*p-value* < 0.001).

	A_f	A_{fs}	A_{s1}
MEAN	0.0305	0.0300	0.3334
SD	0.0418	0.0472	0.7096
SEM	0.0051	0.0058	0.0873
VAR	0.0017	0.0022	0.4959
p-value (A_f *vs* A_{fs})		0.946331	
p-value (A_f *vs* A_{s1})		0.000725	
p-value (A_{s1} *vs* A_{fs})		0.000935	

Spatial Statistics

The optimized hot spot analysis identified statistically significant hot spots and cold spots for fishing effort distribution and for ${}^{S}CPUE$ and *CPUE* for both retained SWO and BIL. However, since this thesis focuses on areas of concentrated PLL fishing effort and areas of relatively higher ${}^{S}CPUE$ and *CPUE* values, only hot spot results (i.e., grid cells with Gi_BIN scores ≥ 2 = 95% confidence) will be presented and discussed.

Using the merged .SHP file of all full set (A_f) polygons, five statistically significant fishing effort distribution hot spots were identified (Figure 12). The two largest were in the SAB and FEC management zones (22,756 and 16,167 km^2, respectively). Two hot spots were identified in the GOM (7,445 and 3,651 km^2), and one hot spot identified in the MAB (3,432 km^2). No hot spots were identified in the NEC management zone. There were 12 hot spots identified for ${}^{S}CPUE$ values of retained SWO (Figure 13A), while only eight hotspots were identified for corresponding *CPUE* values (Figure 13B). Adversely, 11 hot spots were identified for ${}^{S}CPUE$ values of BIL (Figure 14A), while 19 hot spots were identified for corresponding *CPUE* values (Figure 14B). Hot spot areas (km^2) for fishing effort distribution, ${}^{S}CPUE$ and *CPUE* for both BIL and retained SWO by management zone are presented in Table 11.

Using the merged .SHP file for the 2008-2010 subset of full set (Af) polygons in the SAB and FEC, two statistically significant fishing effort distribution hot spots were identified in the SAB and FEC (1,748 and 8,965 km^2, respectively). Additionally, one hot spot of fishing effort was identified within each year. Statistically significant hot spots were identified for ${}^{S}CPUE$ and *CPUE*, for both retained SWO and BIL, collectively and within years 2008-2010. The spatio-temporal relationship between hot spots is thoroughly discussed in the following section. Hot spot areas (km^2) for fishing effort distribution, ${}^{S}CPUE$ and *CPUE* of both BIL and retained SWO for the 2008-2010 subsets are presented in Table 12. All figures for temporal analysis results are referenced in the temporal analysis discussion section.

Table 11. Hot spot areas (km^2) for fishing effort distribution, ${}^{S}CPUE$ and *CPUE* for both BIL and retained SWO by management zone. GOM – Gulf of Mexico; FEC – Florida East Coast; SAB – South Atlantic Bight; MAB – Mid-Atlantic Bight; NEC – Northeast Coastal. Outliers highlighted in red are only associated with one observed PLL set in that location and are not included in the discussion section.

Management Zone	Hotspot Number	Effort	*CPUE*		*SCPUE*	
			SWO	BIL	SWO	BIL
GOM	1	3,651.12	3,760.65	1,009.06	2,535.53	2,454.56
	2	7,445.31	5,480.96	2,247.10	4,429.33	898.23
	3	-	15,262.82	2,113.21	1,196.86	-
	4	-	-	374.37	-	-
	5	-	-	5,221.60	-	-
	6	-	-	2,610.07	-	-
	7	-	-	1,648.33	-	-
	8	-	-	337.40	-	-
FEC	1	16,167.59	6,379.23	31,965.46	928.44	3,986.47
	2	-	-	989.40	-	2,601.78
	3	-	-	989.30	-	977.65
	4	-	-		-	1,001.77
SAB	1	22,756.89	31,247.88	3,254.40	1,670.48	557.35
	2	-	-	1,045.19	2,857.30	-
	3	-	-	3,067.46	-	-
	4	-	-	3,981.36	-	-
MAB	1	3,432.91	2,324.06	1,021.33	562.81	1,209.62
	2	-	862.66	677.61	1,082.52	1,009.23
	3	-	-	733.11	1,032.15	-
	4	-	-	-	784.52	-
NEC	1	-	443.42	1,888.30	1,247.80	2,162.53
	2	-	-	-	2,120.97	2,707.01

Table 12. Hot spot areas (km^2) from 2008-2010 subset for fishing effort distribution, ^{S}*CPUE* and *CPUE* for both BIL and retained SWO in the FEC and SAB management zones. Outliers highlighted in red are only associated with one observed PLL set in that location and are not included in the discussion section.

Year	Hotspot Number	Effort	*CPUE*		^{S}*CPUE*	
			SWO	BIL	SWO	BIL
2008-2010	1	8,965.44	18,539.20	5,285.19	10,952.15	6,728.92
	2	1,748.14	-	8,685.43	774.52	777.64
	3	-	-	784.50	1,005.45	-
	4	-	-	1,000.92	5,008.88	-
2008	1	10,439.39	6,338.31	1,030.37	10,035.82	9,092.78
	2	-	-	4,390.36	864.96	-
	3	-	-	981.49	-	-
2009	1	4,353.65	9,081.34	12,704.90	8,207.13	10,643.51
	2	-	-	-	5,237.58	-
2010	1	4,675.10	5,884.64	4,574.74	4,261.05	778.69
	2	-	-	777.17	767.75	-
	3	-	-	-	934.60	-

Figure 12. Optimized hot spot analysis for fishing effort distribution of all full set (A_f) polygons from the aggregated 2003-2006 and 2008-2010 data sets. Gi_BIN scores are rated -3 – 3, where positive scores reflect hot spots and negative scores reflect cold spots. |1| = 90% confidence; |2| = 95% confidence; |3| = 99% confidence; 0 = not significant (neither a hot spot nor a cold spot).

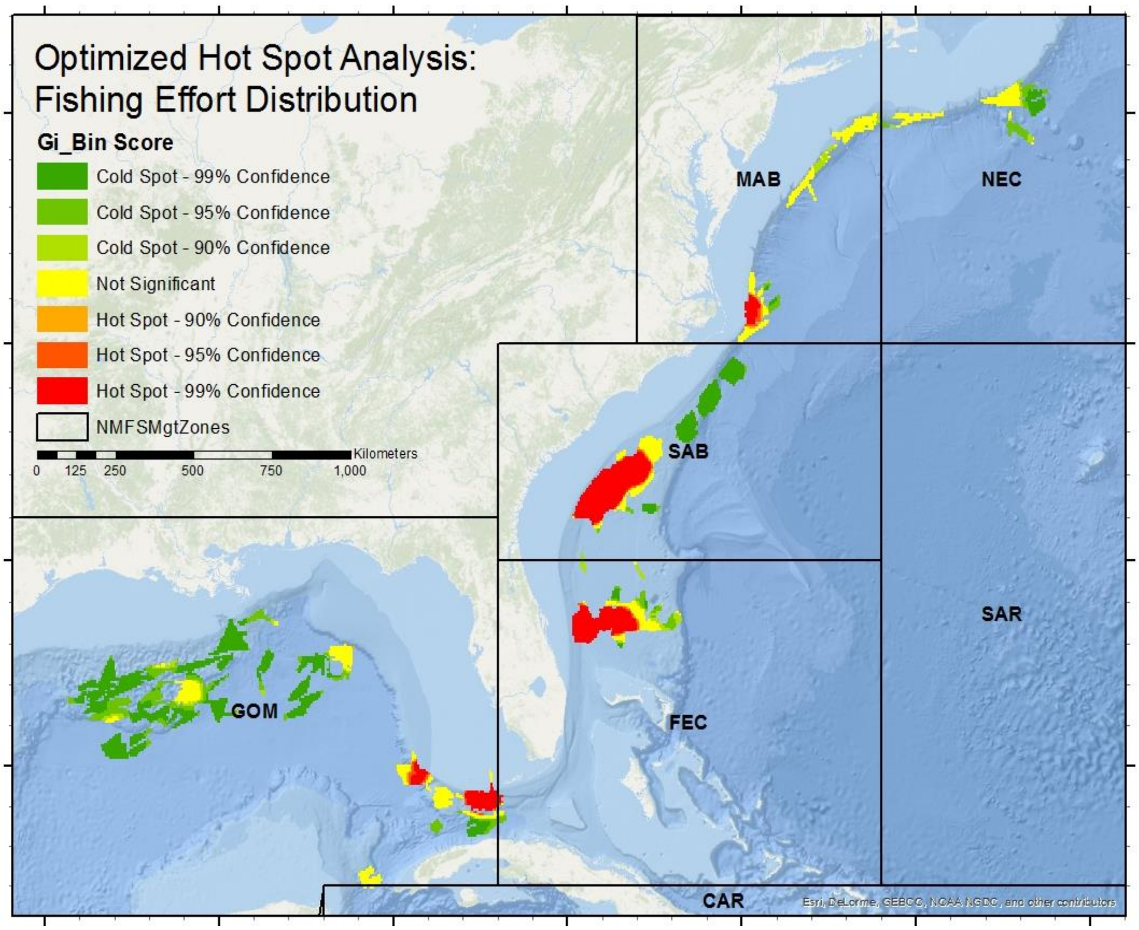


Figure 13A. Optimized hot spot analysis for ${}^{S}CPUE$ of retained SWO for all full set (A_f) polygons from the aggregated 2003-2006 and 2008-2010 data sets. Gi_BIN scores are rated -3 – 3, where positive scores reflect hot spots and negative scores reflect cold spots. |1| = 90% confidence; |2| = 95% confidence; |3| = 99% confidence; 0 = not significant (neither a hot spot nor a cold spot).

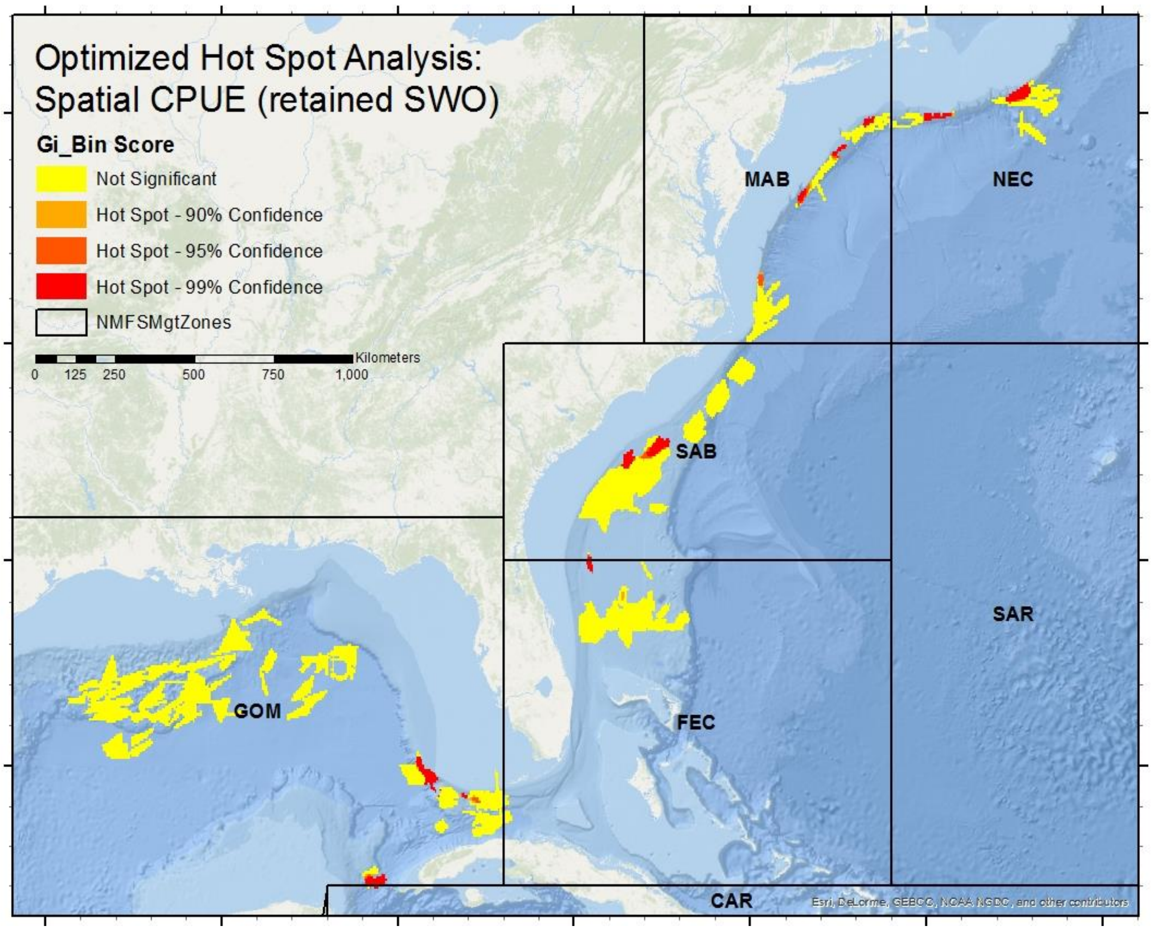


Figure 13B. Optimized hot spot analysis for *CPUE* of retained SWO for all full set (A_f) polygons from the aggregated 2003-2006 and 2008-2010 data sets. Gi_BIN scores are rated -3 – 3, where positive scores reflect hot spots and negative scores reflect cold spots. |1| = 90% confidence; |2| = 95% confidence; |3| = 99% confidence; 0 = not significant (neither a hot spot nor a cold spot).

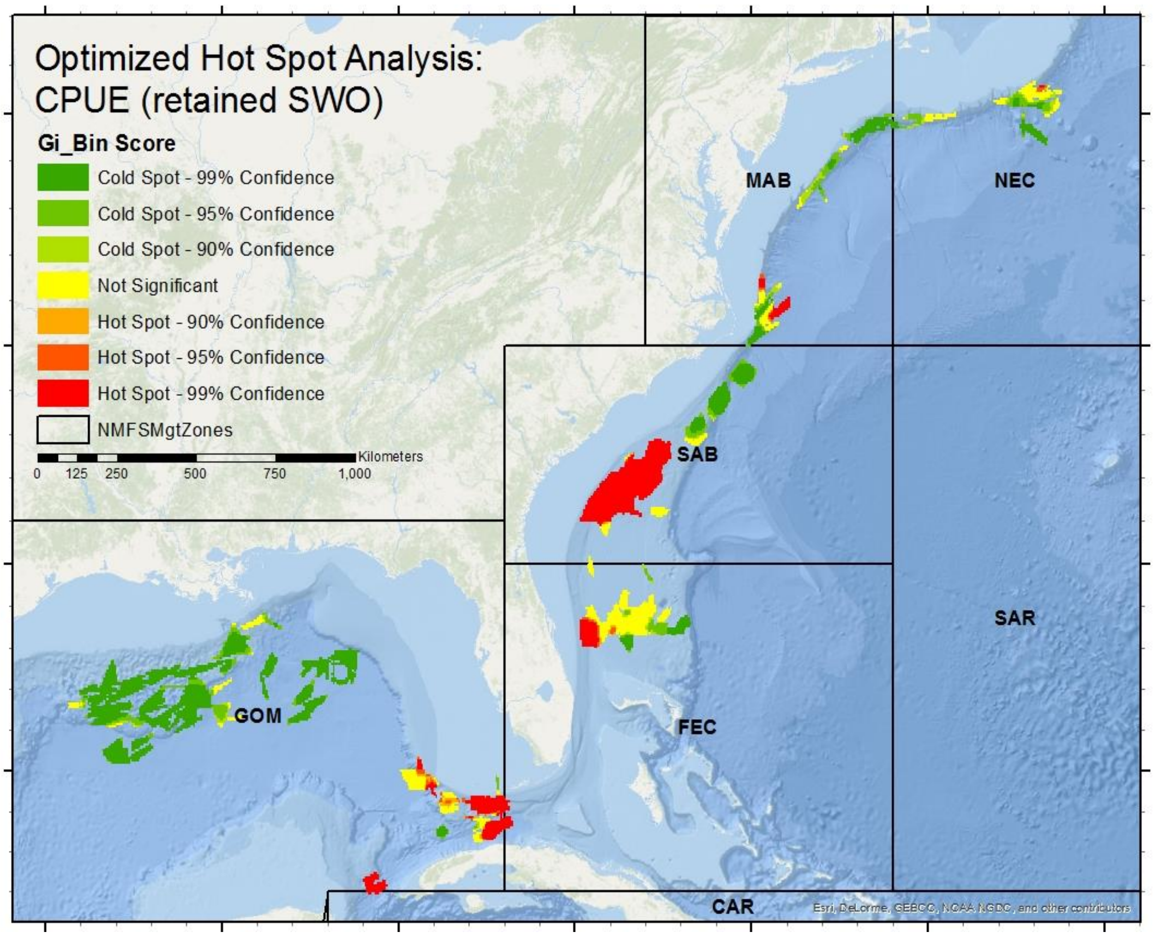


Figure 14A. Optimized hot spot analysis for ${}^{S}CPUE$ of BIL for all full set (A_f) polygons from the aggregated 2003-2006 and 2008-2010 data sets. Gi_BIN scores are rated -3 – 3, where positive scores reflect hot spots and negative scores reflect cold spots. |1| = 90% confidence; |2| = 95% confidence; |3| = 99% confidence; 0 = not significant (neither a hot spot nor a cold spot).

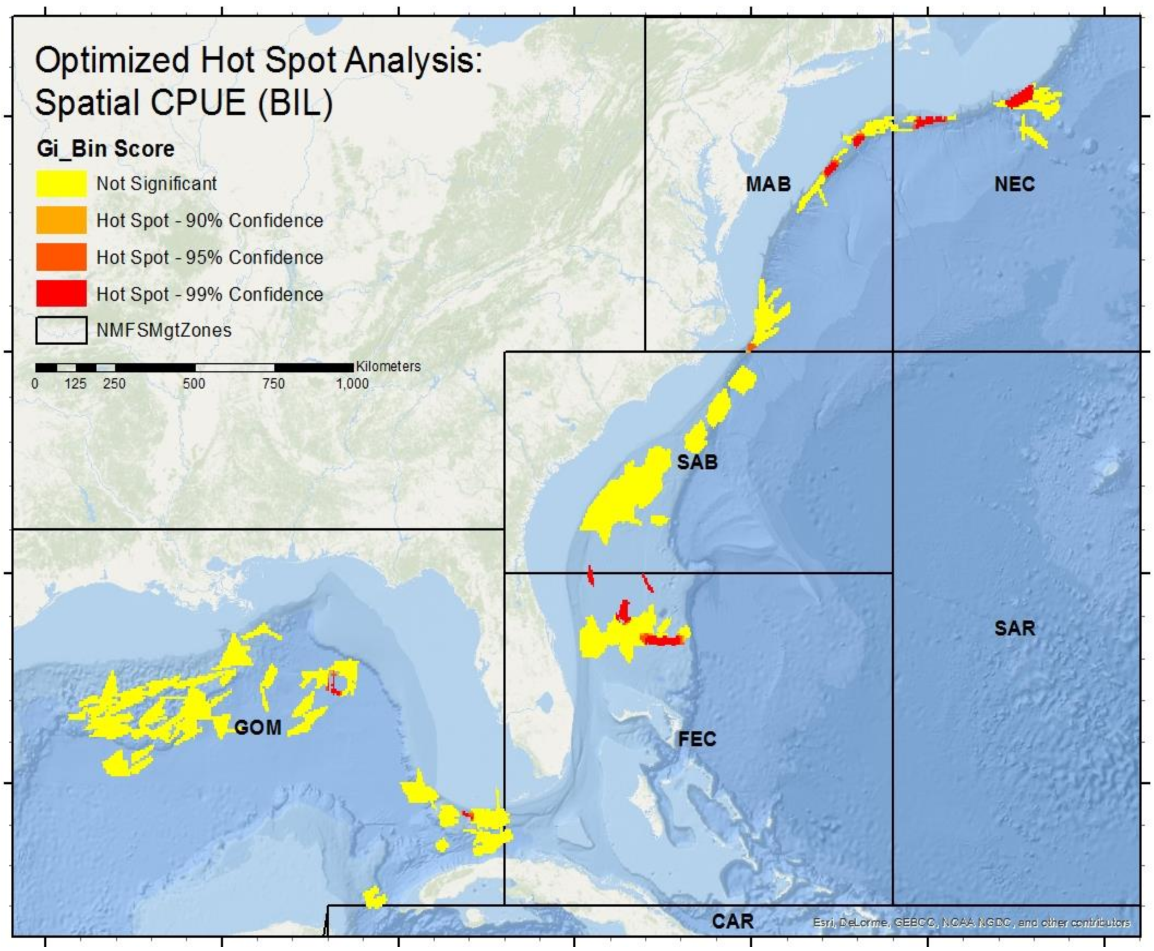
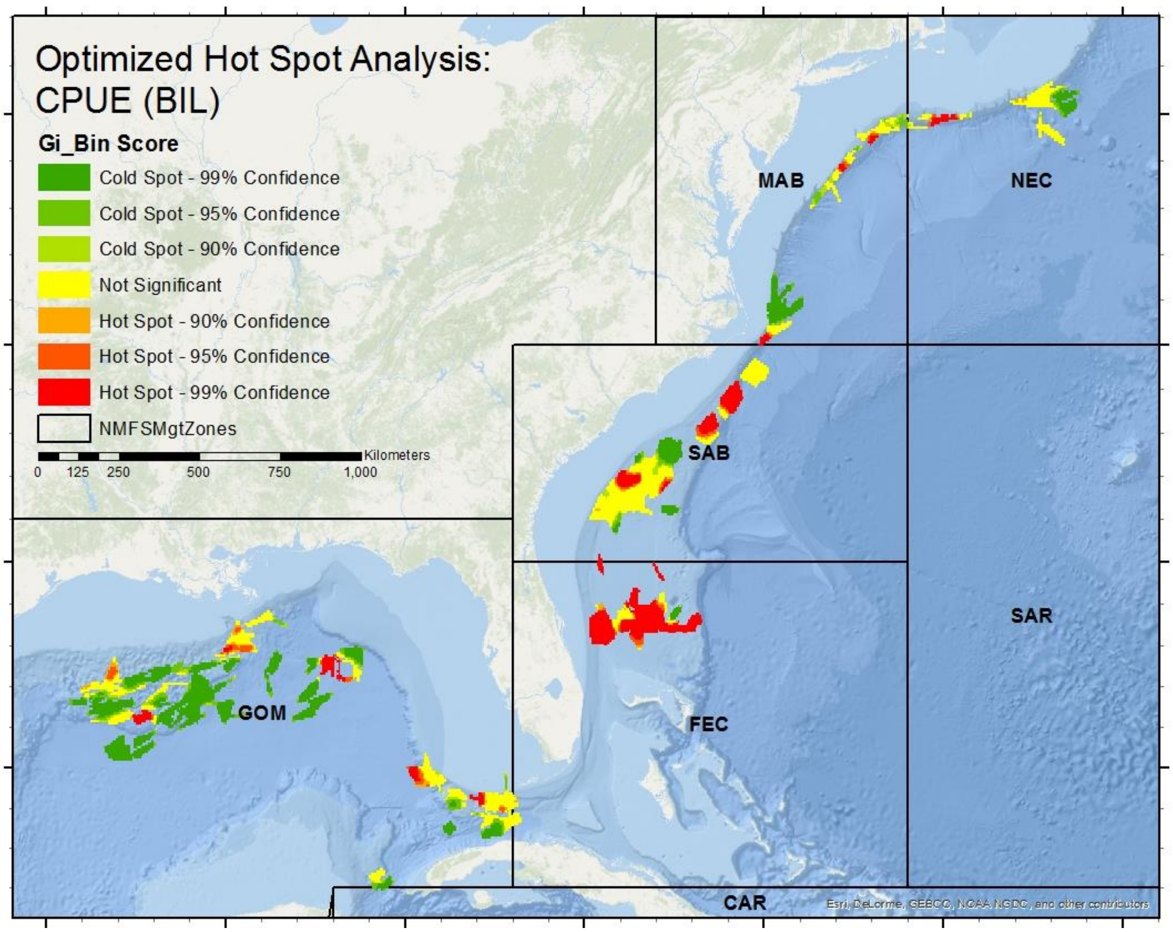


Figure 14B. Optimized hot spot analysis for *CPUE* of BIL for all full set (A_f) polygons from the aggregated 2003-2006 and 2008-2010 data sets. Gi_BIN scores are rated -3 – 3, where positive scores reflect hot spots and negative scores reflect cold spots. |1| = 90% confidence; |2| = 95% confidence; |3| = 99% confidence; 0 = not significant (neither a hot spot nor a cold spot).



Discussion

Non-spatial Analyses

When comparing the full set PAF methods (i.e., the A_f method which uses four coordinates from the start and end of the set and haul, versus A_{fs} which uses the sum of the section areas that create the same set), there was no statistical difference between values ($p > 0.05$). Therefore, although A_{fs} is rarely equal to A_f, the number of cases and degree of difference when it is larger than A_f, and vice versa, is relatively equal. The difference in area between the calculations is more than likely a result of small scale currents acting on the gear in different locations generating various "S" shapes in the mainline or from captains intentionally setting the gear in this manner to cover specific habitat along an oceanic frontal zone. The vertical and horizontal movement of animals hooked during the soak may also influence the shape of the mainline. A_s was significantly different from A_f ($p < 0.001$). Considering a PLL set is composed of sections, this statistical difference was evident prior to analysis even though some full set areas were smaller than section areas on more than a few occasions (e.g., the extremely narrow PLL sets along the shelf break in the MAB). Since no statistical difference was identified between A_f and A_{fs}, A_s was only compared to A_f. Additionally, if ${}^{S}CPUE$ were to be adopted by NMFS, A_f would be the preferred method because current observer data collection protocols and captain logbook requirements only report GPS points at the start and end of the set and haul (section coordinates are only recorded by observers for experimental sets and are not required for captain-reported logbooks).

The distribution of *CPUE* and ${}^{S}CPUE$ values were both positively skewed (S = 2.03 and 9.32, respectively), indicating that both distributions were far from symmetrical and majority of values for both metrics were substantially smaller than the mean (12.66 and 0.043, respectively) and maximum values (95.83 and 1.74, respectively). In fact, over half (57%) of *CPUE* values were less than 10% of the maximum, and an overwhelming majority (95%) of ${}^{S}CPUE$ values were less than 10% of the maximum value (Figures 11A and 11B). Additionally, the kurtosis value for ${}^{S}CPUE$ was twenty times greater than for *CPUE* (K = 104.7 and 5.12, respectively). Since the range of ${}^{S}CPUE$ values was so small (0.17 for 95% of ${}^{S}CPUE$ values compared to 47.9 for 95% of *CPUE*), a fractional change in ${}^{S}CPUE$ would reflect a considerable change in stock abundance if used as an index of relative abundance. Whereas, when *CPUE* is used as an index of relative abundance, a change in stock abundance would be less noticeable. This supports the theory that $^{S}CPUE$ is more accurate than *CPUE* when used as an index of relative abundance by utilizing spatial information obtained directly from the fishing location (Hilborn and Walters 1987 and 1992; Harley et al. 2001; Campbell 2004; Maunder et al. 2006).

Statistical differences existed between the means of $^{S}CPUE$ using the three different PAF calculations (A_f vs. A_{fs} vs. A_s; F = 11.96 > F_{crit}). Further analysis revealed that $^{S}CPUE$ derived via the A_s method was statistically different from both A_f and A_{fs} (p < 0.001) which was consistent with the T-test comparing PAF calculations. Although the number of hooks deployed in each section was proportional to the whole set, the area of each section is highly variable (most likely due to small-scale current effects) and often disproportionally smaller compared to the area of the full set (Table 10). Additionally, the number of animals hooked in each section is not consistent throughout the set. Typically the bulk of animals hooked on any given PLL set come from one or a few sections. This phenomenon stems from the ecology of HMS, many of which exhibit schooling behavior in a large-scale habitat (e.g., tuna species), and the design of PLL gear which effectively targets HMS, among other reasons, by deploying a very long mainline thus increasing the probability of transecting a school of target fish. Assuming standardized deployment (i.e., that buoy configuration, leader length, bait and hook type were the same throughout), the expectation of catching target fish in general is justifiable; however, the expectation to catch target fish in a particular location along the 30 nautical mile-long mainline is questionable. Inevitably, the high variability of $^{S}CPUE$ between neighboring sections, coupled with the migratory behavior of HMS, creates additional uncertainty when interpreting section-level $^{S}CPUE$ as an index for relative abundance.

Optimized Hot Spot Spatial Analysis

Optimized hot spot analyses were conducted to identify areas of high values that were statistically different from a randomized distribution (i.e., areas with Gi_BIN Scores ≥ 2, corresponding to 95% confidence that a hot spot is a “true” hot spot). Full set polygons created via the A_f method were used for analysis since no statistical difference between A_f and A_{fs} methods were identified and both were less variable than the A_s method. Furthermore, the A_f method is more applicable to management due to current observer protocols and captain logbook reporting requirements. For *CPUE* and $^{S}CPUE$, hot spots represent areas of relatively high values compared to neighboring areas and are interpreted as areas where fish tend to aggregate within the area of observed fishing effort. For fishing effort distribution, hot spots represent areas of concentrated fishing effort in terms of relatively high numbers of observed PLL sets compared to neighboring areas and also provide insight into captain behavior towards fishing location. Five statistically significant hot spots of concentrated fishing effort were identified. Refer to Figure 12 for all references to fishing effort distribution hot spots. *CPUE* and $^{S}CPUE$ are expressed using the species three-letter code (plus a letter representing disposition when applicable) as a subscript to the referenced catch rate (e.g., $^{S}CPUE_{SWOr}$ is spatial catch per unit effort for retained swordfish; $CPUE_{BIL}$ is catch per unit effort for Istiophorid species)

South Atlantic Bight (SAB)

The largest fishing effort hot spot was within the South Atlantic Bight (SAB) (22,757 km^2) and extended northward along the 200 m (700 ft) isobath from Jekyll Island, Georgia, to approximately 100 km (62 mi) southeast of Long Bay, South Carolina. The hot spot extended eastward over the northern edge of the Blake Plateau approximately 110 km (68 mi) to a maximum depth of roughly 915 m (3000 ft). The fishing effort hot spot lies completely within the hot spot that was identified for $CPUE_{SWOr}$ (31,248 km^2). In fact, the hot spot for $CPUE_{SWOr}$ extends an additional 100 km east-northeast along the 200 m isobath (Figure 15). Adversely, the hot spots for $^{S}CPUE_{SWOr}$ (Figure 16) are much smaller (1,670 and 2,857 km^2, respectively) and are located almost completely outside the northward boundary of the fishing effort hot spot. Essentially, these explicitly smaller hot spots identify target SWO [i.e., LJFL ≥ 47 in (119 cm), or CK ≥ 25 in (63 cm); Lower Jaw Fork Length (LJFL) – a straight line measurement from the tip of the lower jaw to the fork of the caudal fin; Cleithrum to Caudal Keel – a curved measurement from the cleithrum to the anterior portion of the caudal keel (HMS Commercial Compliance Guide 2014)] aggregations within the distribution of fishing effort. In theory, if vessels concentrated fishing effort in these

Figure 15. $CPUE_{SWOr}$ optimized hot spot analysis in the South Atlantic Bight (SAB) and Florida East Coast (FEC) management zones. Gi_BIN scores are rated -3 – 3, where positive scores reflect hot spots and negative scores reflect cold spots. |1| = 90% confidence; |2| = 95% confidence; |3| = 99% confidence; 0 = not significant (neither a hot spot nor a cold spot). Solid black line delineates boundary between SAB and FEC.

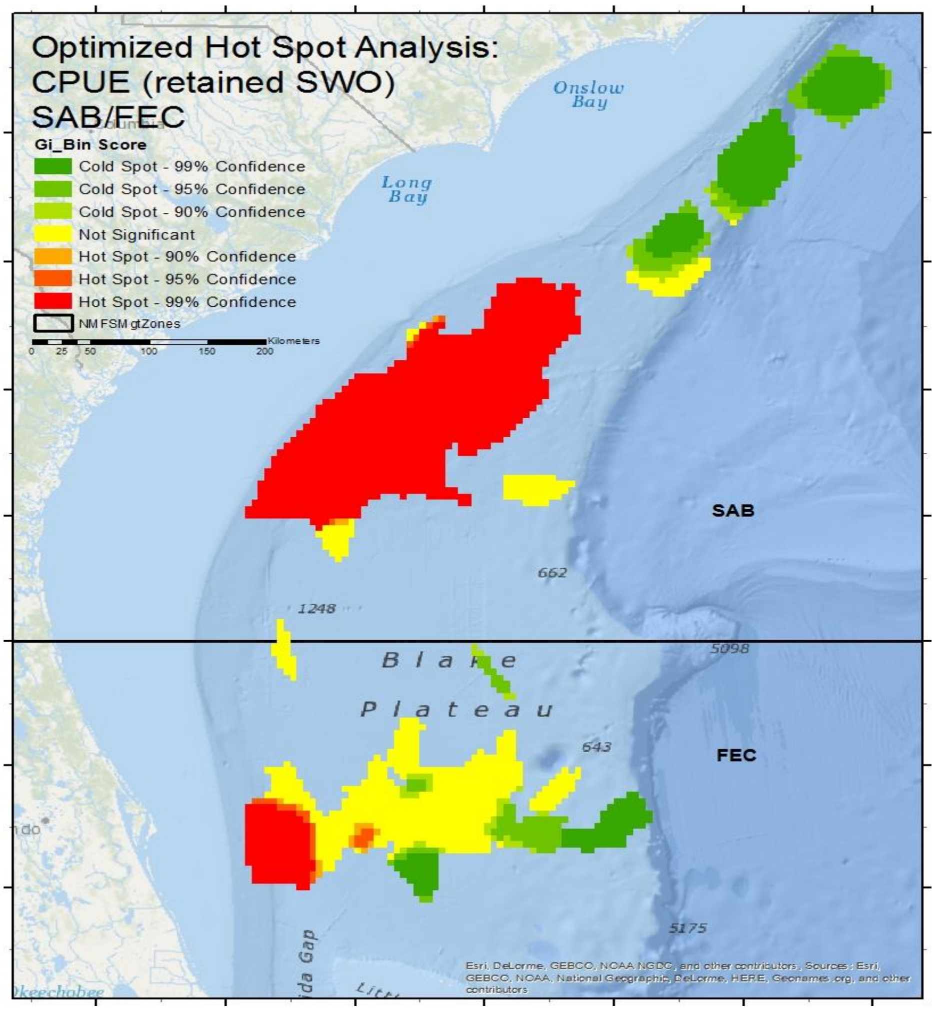
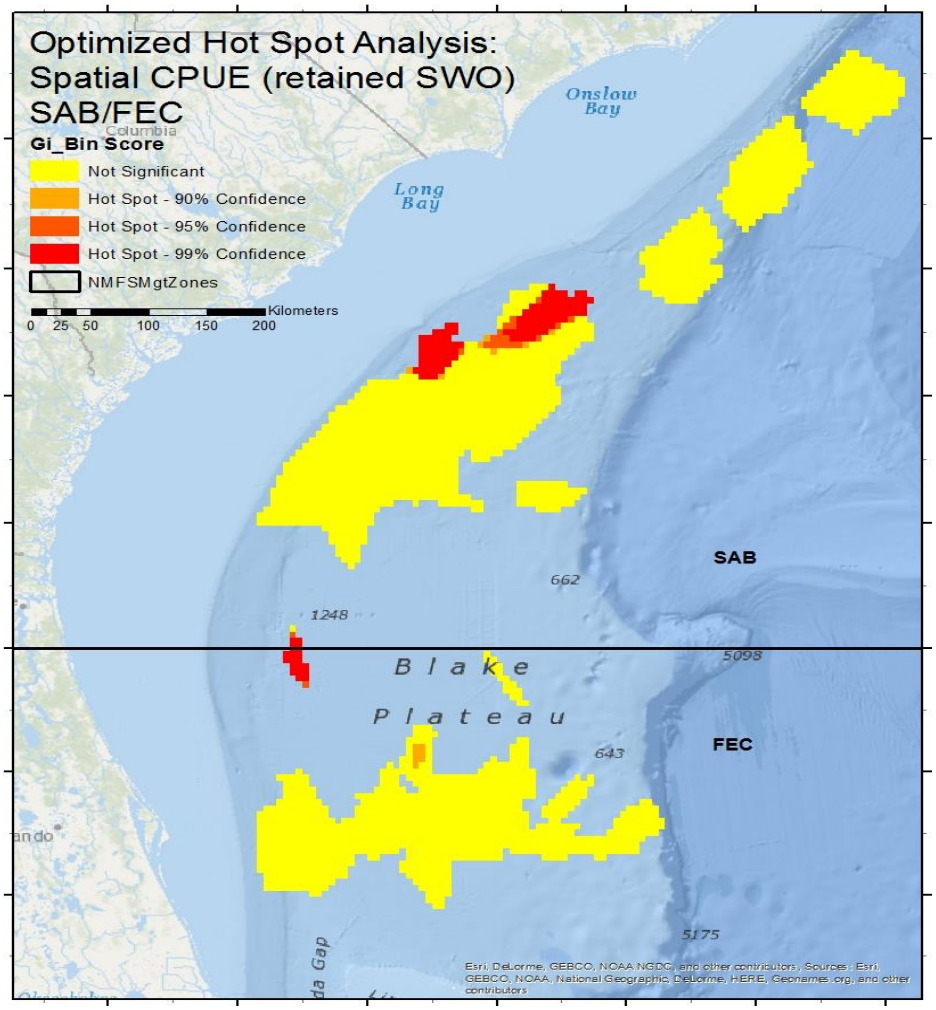


Figure 16. ${}^{S}CPUE_{SWOr}$ optimized hot spot analysis in the South Atlantic Bight (SAB) and Florida East Coast (FEC) management zones. Gi_BIN scores are rated -3 – 3, where positive scores reflect hot spots and negative scores reflect cold spots. |1| = 90% confidence; |2| = 95% confidence; |3| = 99% confidence; 0 = not significant (neither a hot spot nor a cold spot). Solid black line delineates boundary between SAB and FEC.



areas, they would catch more target SWO in less time thus increasing vessel efficiency in terms of profitability. A third hot spot of ${}^{S}CPUE_{SWOr}$ (928 km²) was identified across the SAB and FEC divide, however this is most likely an outlier since only one PLL set was observed there. Additional hot spots were identified in the same location (highlighted in red in the Tables 11 and 12) based on a single PLL set and are omitted from further discussion.

Four $CPUE_{BIL}$ hot spots were identified in the SAB (Figure 17). One (3,254 km²) lies completely within the hot spot for fishing effort along the westward edge. A second, smaller hot spot (1,045 km²) was located adjacent to (and slightly overlapping) the fishing effort hot spot along the northeast boundary of observed fishing effort. Two additional $CPUE_{BIL}$ hot spots (3,067 and 3,981 km²) were identified 20 km (12 mi) apart along the first shelf break approximately 120 km (75 mi) northeast of the fishing effort hot spot extending and extending northward to about 80 km (50 mi) southeast of the northern cape of Onslow Bay, North Caroline. Even though the largest concentration of fishing effort was located in the SAB, no ${}^{S}CPUE_{BIL}$ hot spots were identified there (Figure 18). Therefore, either BIL aggregations are so widely dispersed that no statistically significant hot spots could be identified, or BIL bycatch simply is not a concern for management in the SAB. In either case, ${}^{S}CPUE$ provides further insight pertaining to the location of BIL aggregations (or lack thereof) that would not have otherwise been identified using the current $CPUE$ metric.

Florida East Coast (FEC)

The second largest fishing effort hot spot (16,168 km^2) was within the Florida East Coast (FEC) management zone. The hot spot's westward edge is located approximately 75 km (46 mi) due east of Cape Canaveral, Florida, where depths drop from 250 m (820 ft) to over 600 m (2000 ft). The hot spot continues eastward over the Blake Plateau for approximately 150 km (93 mi) to a depth of over 1000 m (3280 ft). One $CPUE_{SWOr}$ hot spot (6,379 km^2) was identified along the westward edge of the fishing effort hot spot (Figure 15). Similar to the case of ${}^{S}CPUE_{BIL}$ in the SAB, zero ${}^{S}CPUE_{SWOr}$ hot spots for were identified in the FEC (Figure 16). Within the context of this data set, the lack of ${}^{S}CPUE$ hot spots suggests that SWO are currently harvested (and

BIL are currently avoided) in the most economically sustainable way possible with PLL gear in this geographic region.

One very large $CPUE_{BIL}$ hot spot (31,965 km^2; Figure 17) was identified in the FEC and completely encompasses all of the observed fishing effort, and two $^{S}CPUE_{BIL}$ hot spots (Figure 18) were identified within that hot spot along the northward (3,986 km^2) and southeastward (2,602 km^2) boundaries. Vessels may wish to avoid operating in those particular areas due to increased BIL aggregations. Concentrating fishing efforts outside of these areas would decrease BIL interactions thus providing the greatest opportunity to catch target fish (i.e., fewer hooks and/or bait consumed by billfish). Fortunately, these two hot spots are located outside the area of concentrated fishing effort, suggesting that PLL vessels are already actively minimizing BIL interactions in this geographic region assuming observer presence does not effect vessel fishing location.

Figure 17. $CPUE_{BIL}$ optimized hot spot analysis in the South Atlantic Bight (SAB) and Florida East Coast (FEC) management zones. Gi_BIN scores are rated -3 – 3, where positive scores reflect hot spots and negative scores reflect cold spots. |1| = 90% confidence; |2| = 95% confidence; |3| = 99% confidence; 0 = not significant (neither a hot spot nor a cold spot). Solid black line delineates boundary between SAB and FEC.

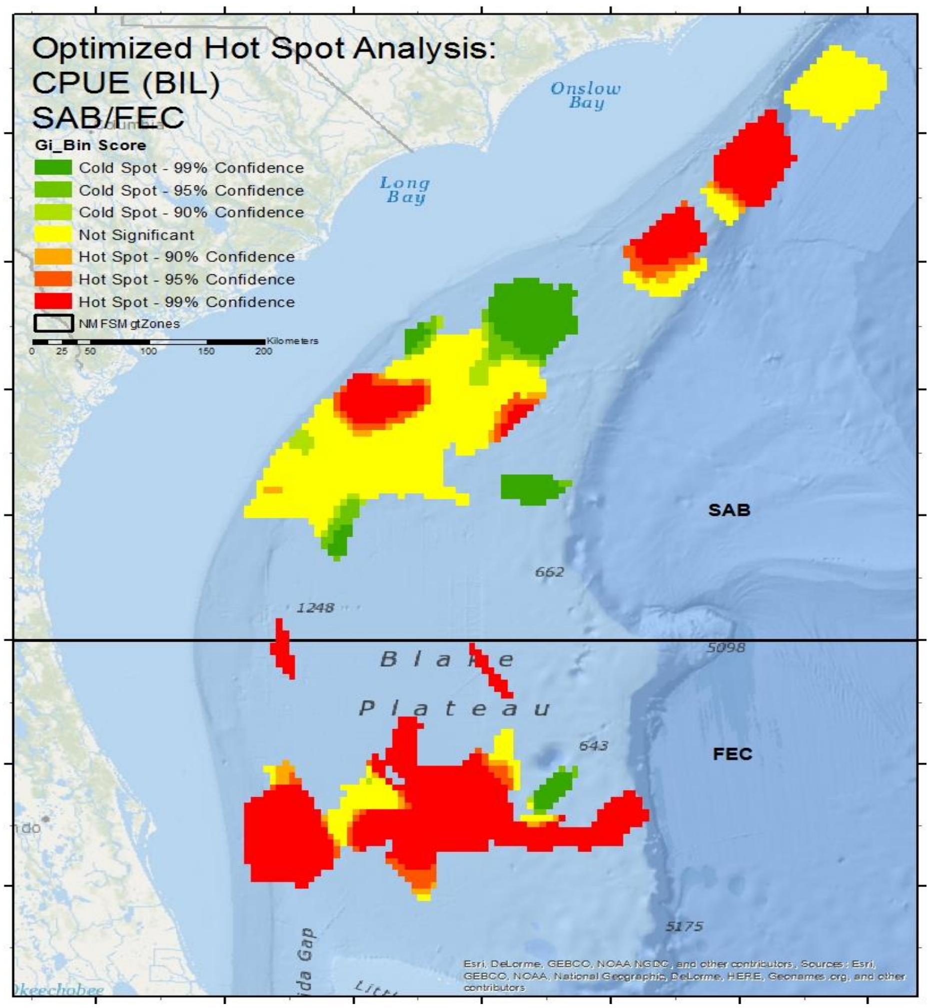
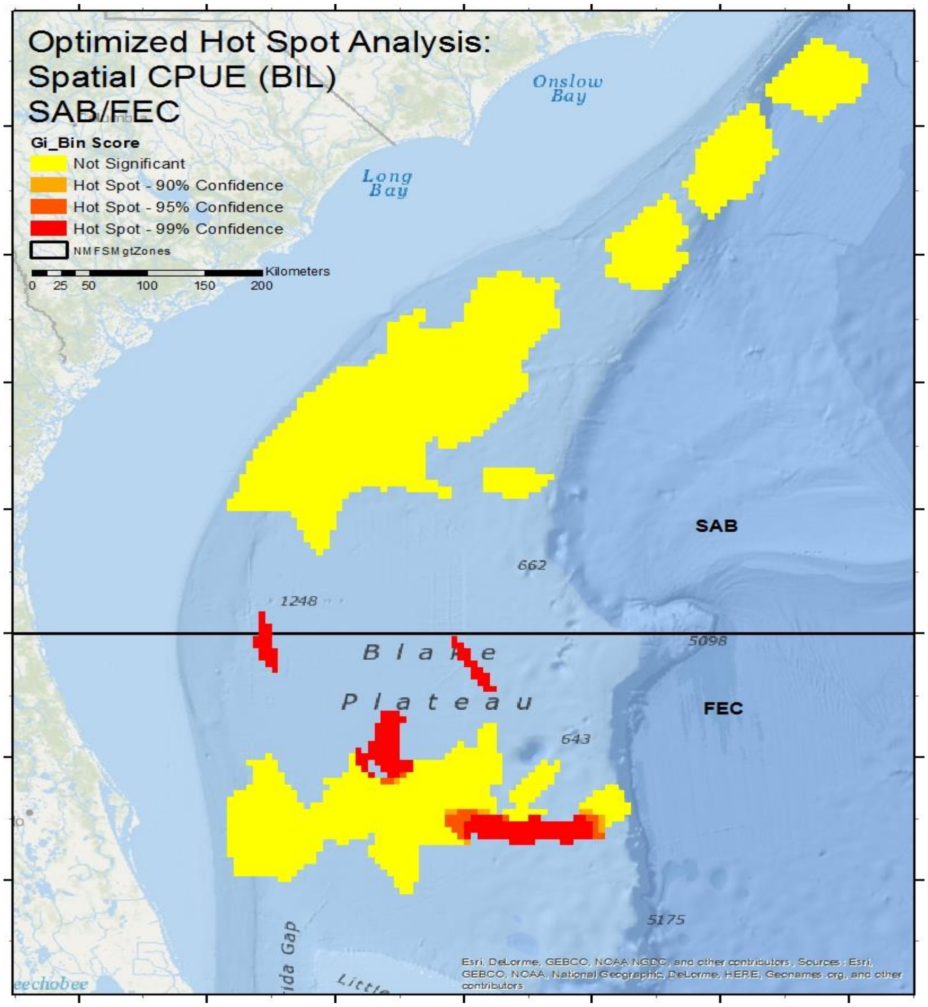


Figure 18. $^{S}CPUE_{BIL}$ optimized hot spot analysis in the South Atlantic Bight (SAB) and Florida East Coast (FEC) management zones. Gi_BIN scores are rated -3 – 3, where positive scores reflect hot spots and negative scores reflect cold spots. |1| = 90% confidence; |2| = 95% confidence; |3| = 99% confidence; 0 = not significant (neither a hot spot nor a cold spot). Solid black line delineates boundary between SAB and FEC.



Gulf of Mexico (GOM)

Two much smaller fishing effort hot spots were identified in the Gulf of Mexico (GOM). Although PLL effort was the most widely distributed visually in the GOM compared to other management zones, the two hot spots were identified only 100 km (46 mi) apart. It is important to note, however, that most PLL effort in the northern Gulf of Mexico was targeting YFT, which employs slightly different techniques (e.g., bait type, space between gangions, fishing depth) compared to targeting SWO. The larger of the two hot spots (7,445 km^2) was located just south of the Dry Tortugas extending southward from the shelf break to the Mitchell Escarpment at an approximate depth of 1,100 m (3,600 ft). The smaller hot spot (3,651 km^2) was located roughly 100 km (46 mi) west of the Dry Tortugas and is situated over a series of canyons, including the Florida Canyon, at the southern edge of the West Florida Escarpment.

Two $CPUE_{SWOr}$ hot spots were identified in the GOM (Figure 19). The first (5,481 km^2) overlaps the eastward side of the northern fishing effort hot spot, extending north and south an additional 10-20 km (6-12 mi) along the shelf break. The second $CPUE_{SWOr}$ hot spot (15,263 km^2) completely encompasses the southern fishing effort hot spot and extends into deeper waters some 20 km (12 mi) north of Havana, Cuba, and continuing eastward over the GOM/FEC management zone divide. A third $CPUE_{SWOr}$ hot spot (3,761 km^2) was identified approximately 100 km (46 mi) west of the Gulfo de Guanahacabibes, Cuba, and is situated over the southern edge of the Tulum Terrace at approximately 1000 m (3280 ft) depth. Concurrently, three ${}^{S}CPUE_{SWOr}$ were identified in the same locations (Figure 20). The hot spot coinciding with the series of canyons at the southern edge of the West Florida Escarpment is roughly the same area (4,429 km^2) and location as the $CPUE_{SWOr}$ hot spot. This probably is not coincidental, and more likely a result of experienced captains who have targeted SWO in these waters for many years and continue to pass that knowledge to current and future generations of PLL fishermen. The hot spot coinciding with the area over the Tulum Terrace is smaller (2,536 km^2) than the hot spot for $CPUE_{SWOr}$ and overlaps the southern portion, implying that the southern portion may warrant additional monitoring due to aggregations of target SWO. The last, and smallest, ${}^{S}CPUE_{SWOr}$ hot spot (1,197 km^2) in the GOM is situated directly over the Tortugas Terrace and Valley at the northwest corner of the $CPUE_{SWOr}$ and fishing effort hot spots. This hot spot is significantly smaller than other hot spots in the region indicating that fishermen may wish to concentrate their efforts here in order to take advantage of the small-scale area where target SWO aggregate.

Three $CPUE_{BIL}$ hot spots were identified in the GOM (Figure 21) that correlate with fishing effort hot spots and an additional five were identified in the northern GOM, south of the shelf edge, scattered across the ridges, valleys and escarpments of the continental slope. However, only two $^{S}CPUE_{BIL}$ hot spots were identified here (Figure 22). The smaller of the two is situated over the Tortugas Terrace and Valley, similar to the $^{S}CPUE_{SWOr}$ hot spot mentioned above. The larger $^{S}CPUE_{BIL}$ hot spot (2,455 km^2), and the largest $CPUE_{BIL}$ hot spot (5,222 km^2), is located near the De Soto Canyon, an area which was closed off to PLL gear in November of 2000 in order to reduce incidental catch of undersized SWO (SAFE 2014). Since this area is historically identified for undersized SWO, it makes sense that it is not a hot spot for retained SWO, but is still frequented by PLL vessels due to occasional legal-sized individuals. Nevertheless, $^{S}CPUE_{BIL}$ identifies two particular areas of concern in terms of BIL bycatch that would not otherwise be identified with current *CPUE* spatial-referencing methods.

Figure 19. $CPUE_{SWOr}$ optimized hot spot analysis in the Gulf of Mexico (GOM) management zones. Gi_BIN scores are rated -3 – 3, where positive scores reflect hot spots and negative scores reflect cold spots. |1| = 90% confidence; |2| = 95% confidence; |3| = 99% confidence; 0 = not significant (neither a hot spot nor a cold spot). Solid black line delineates boundary between management zones.

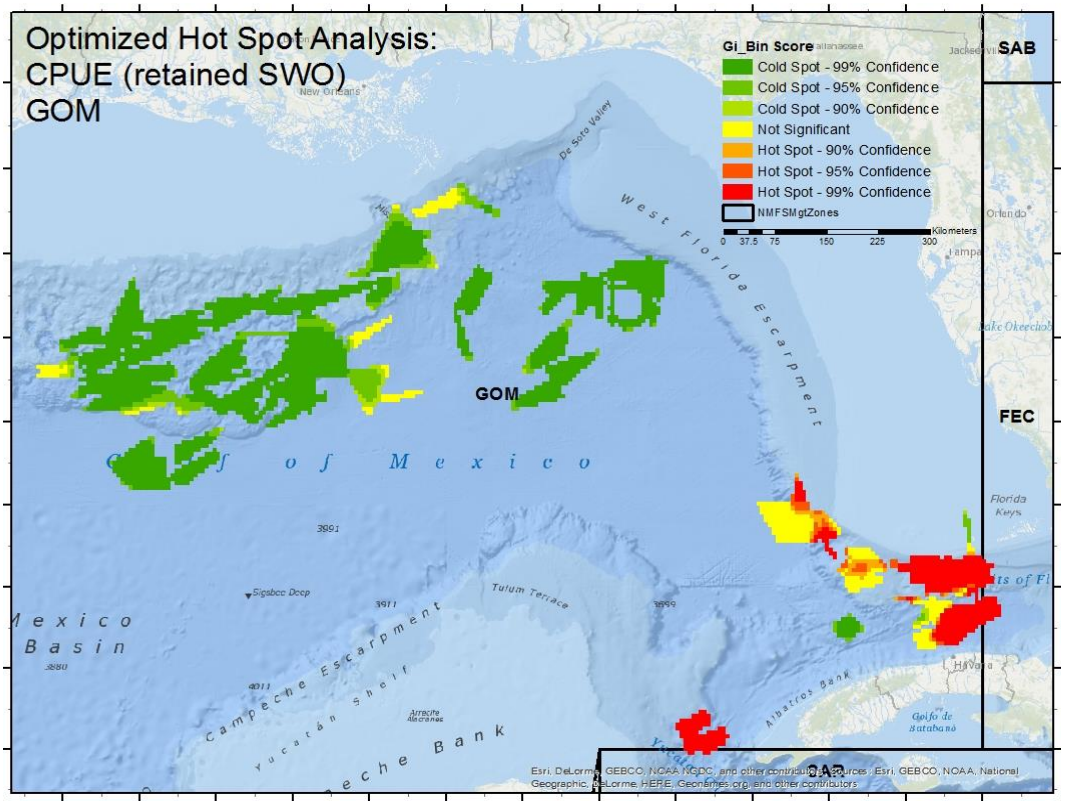


Figure 20. $^{S}CPUE_{SWOr}$ optimized hot spot analysis in the Gulf of Mexico (GOM) management zones. Gi_BIN scores are rated -3 – 3, where positive scores reflect hot spots and negative scores reflect cold spots. |1| = 90% confidence; |2| = 95% confidence; |3| = 99% confidence; 0 = not significant (neither a hot spot nor a cold spot). Solid black line delineates boundary between management zones.

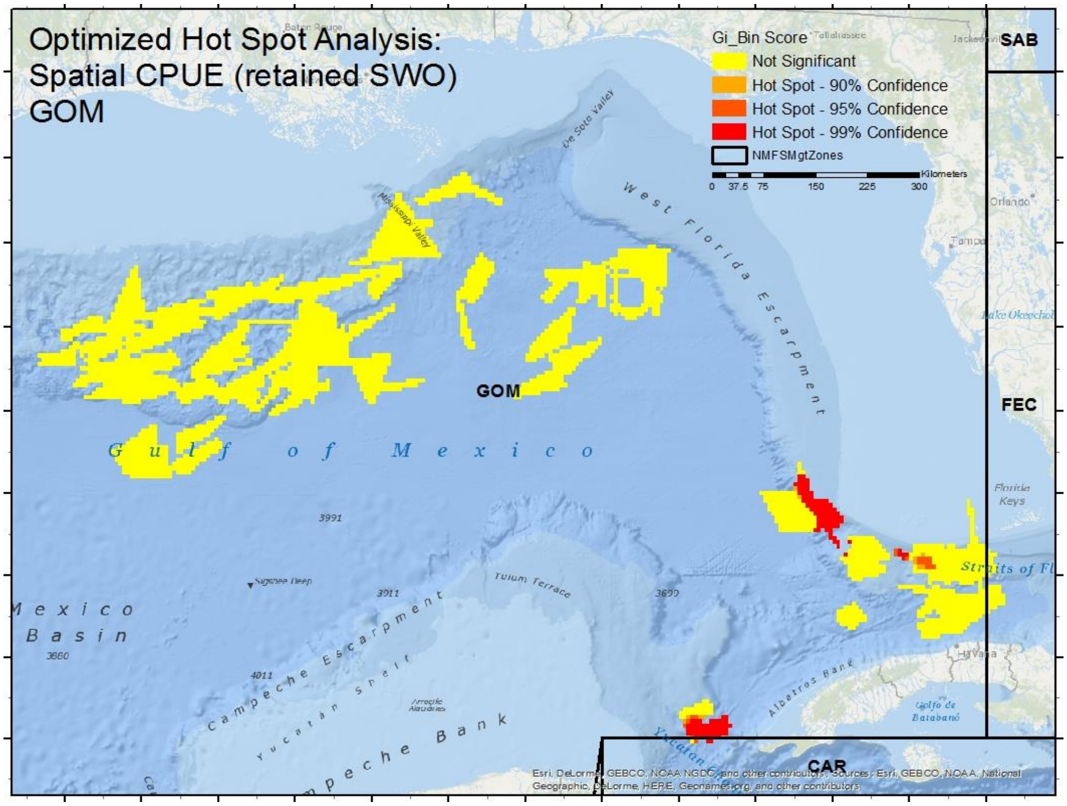


Figure 21. $CPUE_{BIL}$ optimized hot spot analysis in the Gulf of Mexico (GOM) management zones. Gi_BIN scores are rated -3 – 3, where positive scores reflect hot spots and negative scores reflect cold spots. |1| = 90% confidence; |2| = 95% confidence; |3| = 99% confidence; 0 = not significant (neither a hot spot nor a cold spot). Solid black line delineates boundary between management zones.

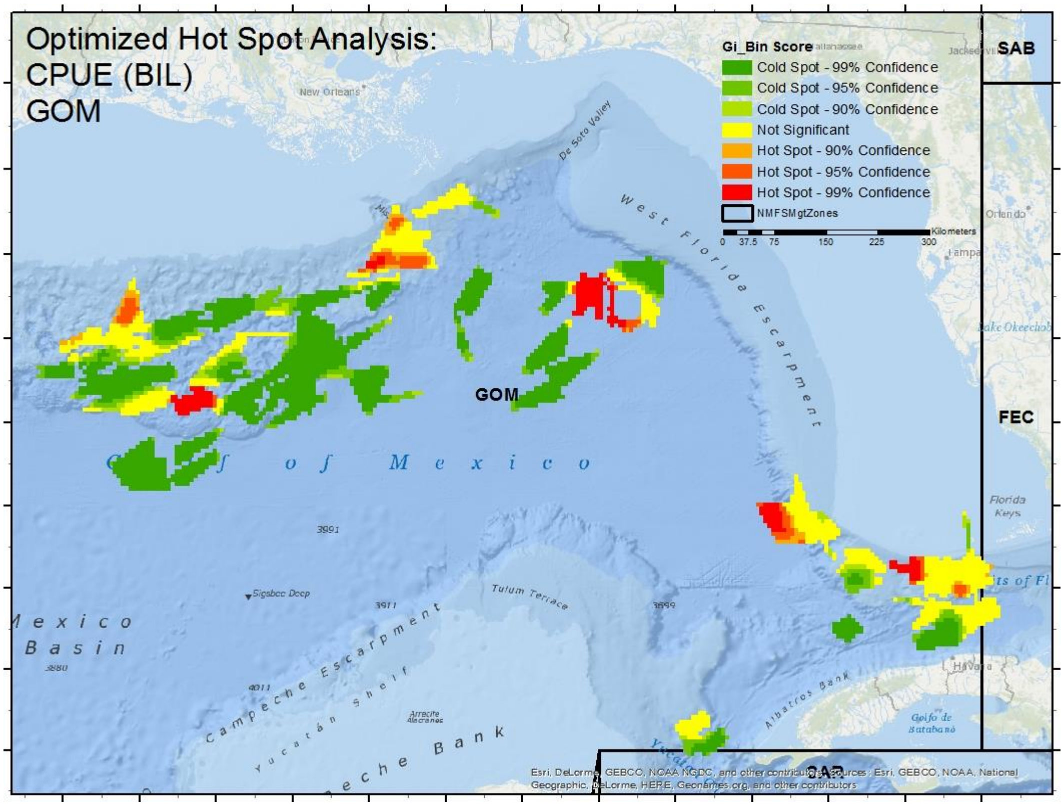
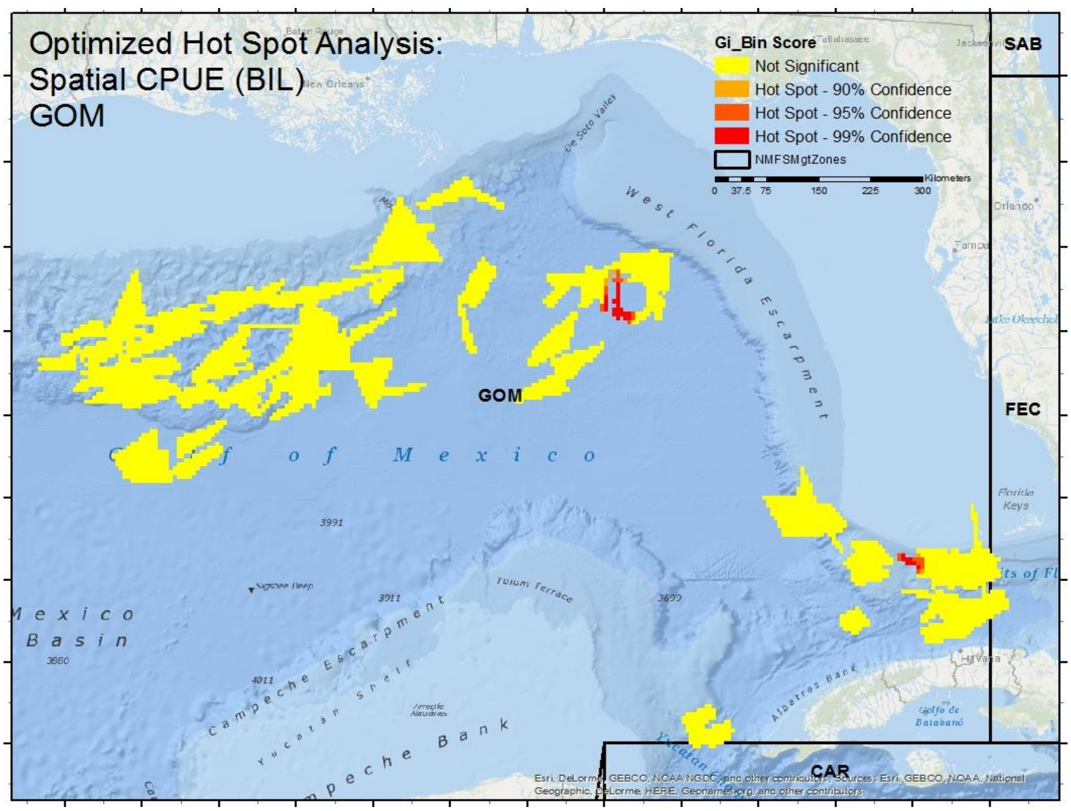


Figure 22. $^{S}CPUE_{BIL}$ optimized hot spot analysis in the Gulf of Mexico (GOM) management zones. Gi_BIN scores are rated -3 – 3, where positive scores reflect hot spots and negative scores reflect cold spots. |1| = 90% confidence; |2| = 95% confidence; |3| = 99% confidence; 0 = not significant (neither a hot spot nor a cold spot). Solid black line delineates boundary between management zones.



Mid-Atlantic Bight (MAB) and Northeast Coastal (NEC)

The smallest fishing effort hot spot was identified in the Mid-Atlantic Bight (MAB) (3,433 km^2) situated over a series of canyons approximately 60 km (37) east-northeast of Pamlico Sound. No fishing effort hot spots were identified in the Northeast Coastal (NEC) management zone. Unlike within other management zones, where *CPUE* and $^{S}CPUE$ hot spots were generally in close proximity to a fishing effort hot spot, there was very little association with fishing effort hot spots in the MAB and NEC. One $CPUE_{BIL}$ (Figure 23) and one $^{S}CPUE_{BIL}$ (Figure 24) hot spot was identified in association with the fishing effort hot spot (both were situated just south of the hot spot along the shelf break). The rest of the hot spots generally coincided with each other and were sporadically spaced along the shelf break east of New Jersey and south of the Georges Bank. There were three $CPUE_{SWOr}$ (Figure 25) hot spots identified. Two were identified in association with the fishing effort hot spot; one situated just north (863 km^2) and the other just east (2,324 km^2). The third hot spot (443 km^2) is located near the northwestward edge of observed fishing effort in the NEC. Six $^{S}CPUE_{SWOr}$ hot spots (Figure 26) were identified in the MAB and NEC. Only one is situated in close proximity to the fishing effort hot spot while the other five are sporadically spaced along the shelf break similar to both BIL hot spots.

Fishing effort in the MAB and NEC was observed over a series of canyons cutting diagonally through the management zones along the shelf break. The PAF of PLL sets in this region were characteristically narrower compared to other regions and seemingly strategically set to minimize east-west drift and maximize fishing time over the canyons during the soak. According to the location of $^{S}CPUE$ hot spots, it was inferred that BIL and target SWO aggregate in and around specific canyons based on habitat suitability requirements (e.g., bathymetry, surface and bottom currents, prey availability). Vessels could increase catch of target SWO by concentrating fishing efforts near canyons associated with $^{S}CPUE$ hot spots.

Figure 23. $CPUE_{SWOr}$ optimized hot spot analysis in the Mid-Atlantic Bight (MAB) and Northeast Coastal (NEC) management zones. Gi_BIN scores are rated -3 – 3, where positive scores reflect hot spots and negative scores reflect cold spots. |1| = 90% confidence; |2| = 95% confidence; |3| = 99% confidence; 0 = not significant (neither a hot spot nor a cold spot). Solid black line delineates boundary between management zones.

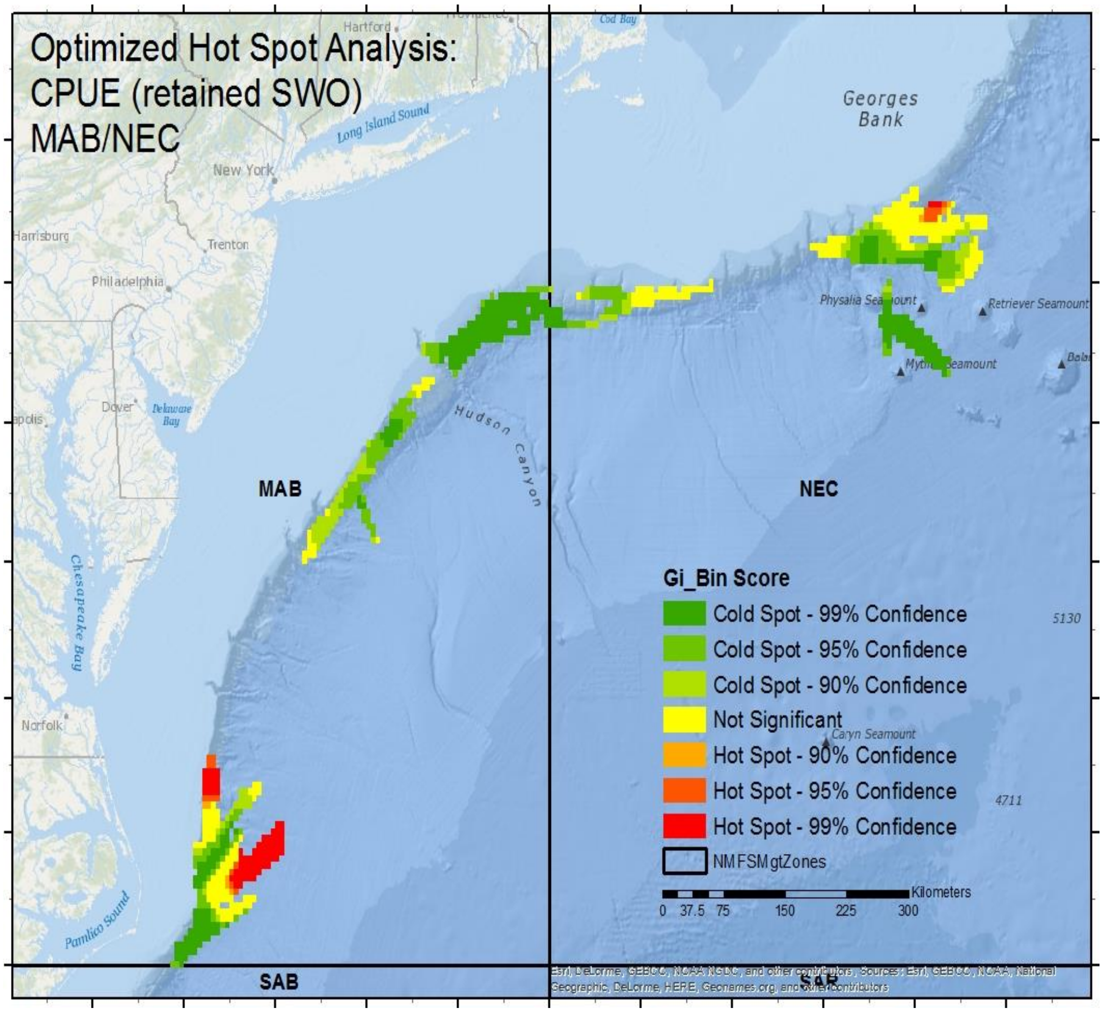


Figure 24. $^{S}CPUE_{SWOr}$ optimized hot spot analysis in the Mid-Atlantic Bight (MAB) and Northeast Coastal (NEC) management zones. Gi_BIN scores are rated -3 – 3, where positive scores reflect hot spots and negative scores reflect cold spots. |1| = 90% confidence; |2| = 95% confidence; |3| = 99% confidence; 0 = not significant (neither a hot spot nor a cold spot). Solid black line delineates boundary between management zones.

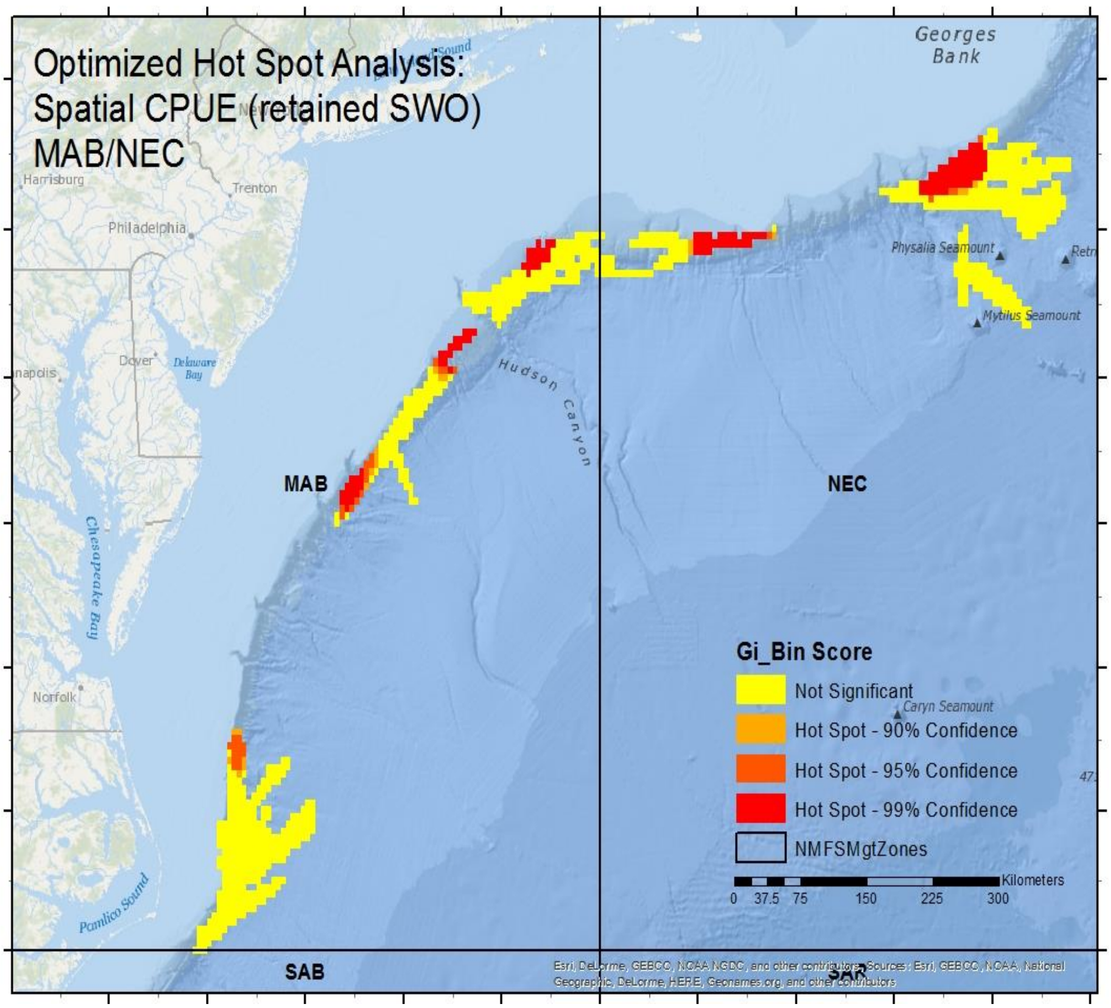


Figure 25. $CPUE_{BIL}$ optimized hot spot analysis in the Mid-Atlantic Bight (MAB) and Northeast Coastal (NEC) management zones. Gi_BIN scores are rated -3 – 3, where positive scores reflect hot spots and negative scores reflect cold spots. |1| = 90% confidence; |2| = 95% confidence; |3| = 99% confidence; 0 = not significant (neither a hot spot nor a cold spot). Solid black line delineates boundary between management zones.

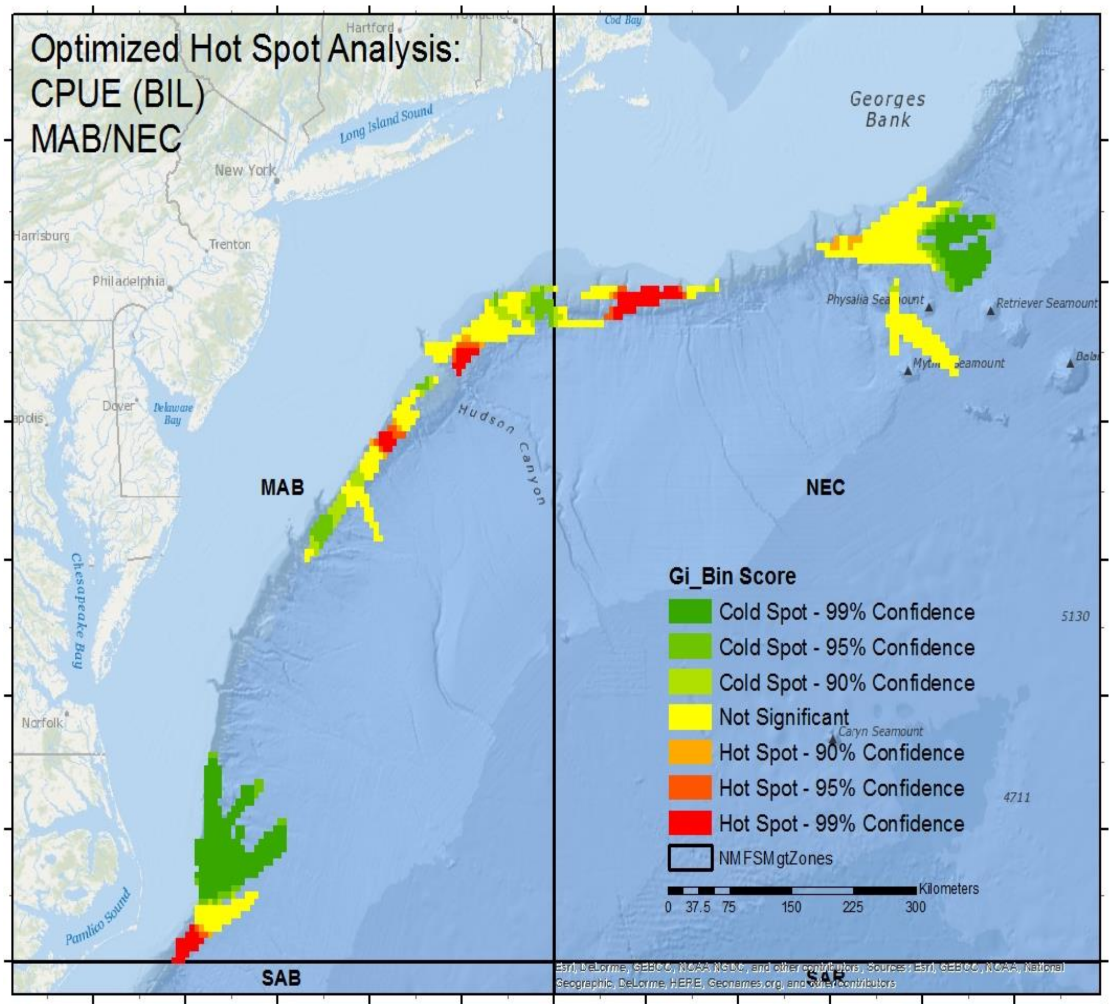
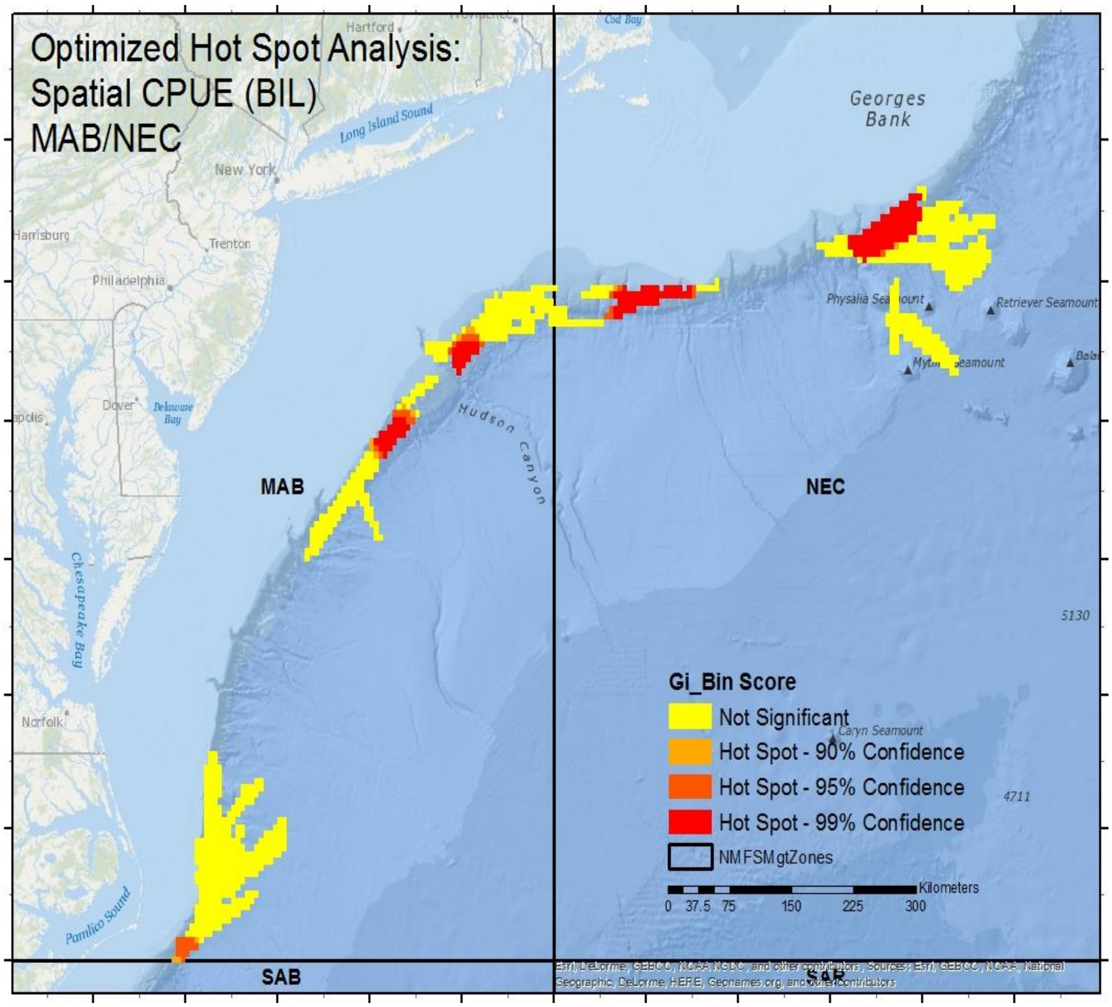


Figure 26. $^{S}CPUE_{BIL}$ optimized hot spot analysis in the Mid-Atlantic Bight (MAB) and Northeast Coastal (NEC) management zones. Gi_BIN scores are rated -3 – 3, where positive scores reflect hot spots and negative scores reflect cold spots. |1| = 90% confidence; |2| = 95% confidence; |3| = 99% confidence; 0 = not significant (neither a hot spot nor a cold spot). Solid black line delineates boundary between management zones.



Temporal Analysis

In regards to HMS management, identifying temporal changes in hot spot locations is arguably as important as identifying the location of hot spots themselves. The location of hot spots derived from aggregated catch and effort data over several years provides tangible insight to where HMS may be aggregating within a large-scale habitat, such as the Atlantic Ocean. Temporal analysis provides inter- and intra-annual habitat preference information which reflects migratory paths, or ontogenetic shifts, between feeding and spawning locations. The best science leading to effective and sustainable HMS management stems from analyzing both the temporal and spatial relationship between fishing effort distribution and *CPUE* hot spots simultaneously. The 2008-2010 subsets were used to qualitatively discuss the temporal movement of fishing effort distribution and of both standard and spatial *CPUE* hot spots. PLL sets from these years were observed in conjunction with NMFS East Florida Coast Time-Area Closure study which mandated 100% observer coverage in the region. Accordingly, all PLL sets from the 2008-2010 subset were observed in the FEC and SAB (Figure 9B) providing an opportunity within this dataset to qualitatively examine temporal changes in hot spot location.

Two fishing effort distribution hot spots were identified in the aggregated 2008-2010 subset (Figure 27). The larger hot spot (8,965 km^2) was situated in the same location as the fishing effort hot spot that was identified in the FEC mentioned previously, except it is half the size and only occupies the western portion. The smaller hot spot (1,748 km^2) is located over the first shelf break approximately 150 km (93 mi) east of Savannah, Georgia, in the SAB where depths drop from 250 m (820 ft) to over 600 m (2000 ft). Two $CPUE_{BIL}$ hot spots were identified and both are located in the FEC (Figure 28). The first (5,285 km^2) lies completely within the fishing effort hot spot and the other (8,685 km^2) is located roughly 50 km (30 mi) east within the same latitudes. Only one ${}^{S}CPUE_{BIL}$ hot spot (6,729 km^2) was identified (Figure 29) and is associated with the latter $CPUE_{BIL}$ hot spot occupying the southern portion. Adversely, one large $CPUE_{SWOr}$ hot spot (18,539 km^2) was identified in the SAB (Figure 30), and is situated northeast of the fishing effort hot spot approximately 120 km (75 mi) from coastal Long Bay, South Carolina, along the first shelf break. One ${}^{S}CPUE_{SWOr}$ hot spot was identified

Figure 27. 2008-2010 fishing effort optimized hot spot analysis in the South Atlantic Bight (SAB) and Florida East Coast (FEC) management zones. Gi_BIN scores are rated -3 – 3, where positive scores reflect hot spots and negative scores reflect cold spots. |1| = 90% confidence; |2| = 95% confidence; |3| = 99% confidence; 0 = not significant (neither a hot spot nor a cold spot). Solid black line delineates boundary between management zones.

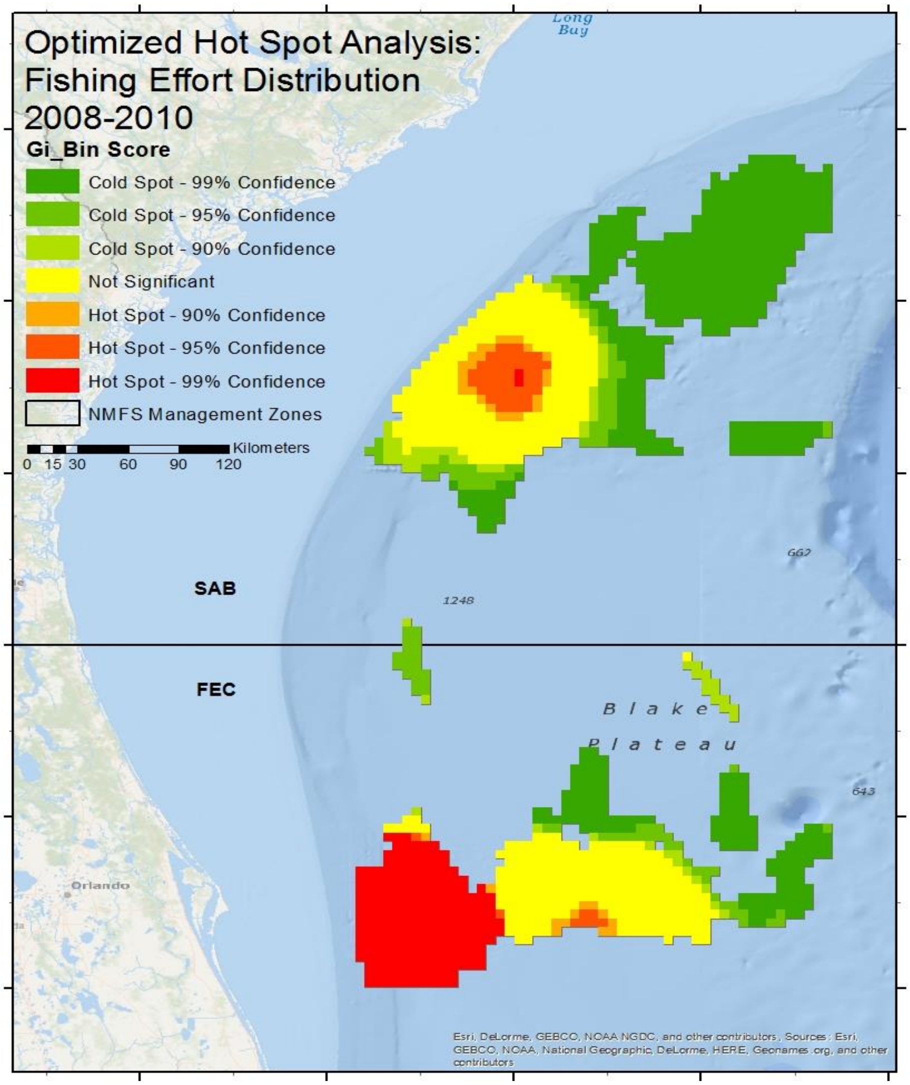


Figure 28. 2008-2010 $CPUE_{SWOr}$ optimized hot spot analysis in the South Atlantic Bight (SAB) and Florida East Coast (FEC) management zones. Gi_BIN scores are rated -3 – 3, where positive scores reflect hot spots and negative scores reflect cold spots. |1| = 90% confidence; |2| = 95% confidence; |3| = 99% confidence; 0 = not significant (neither a hot spot nor a cold spot). Solid black line delineates boundary between management zones.

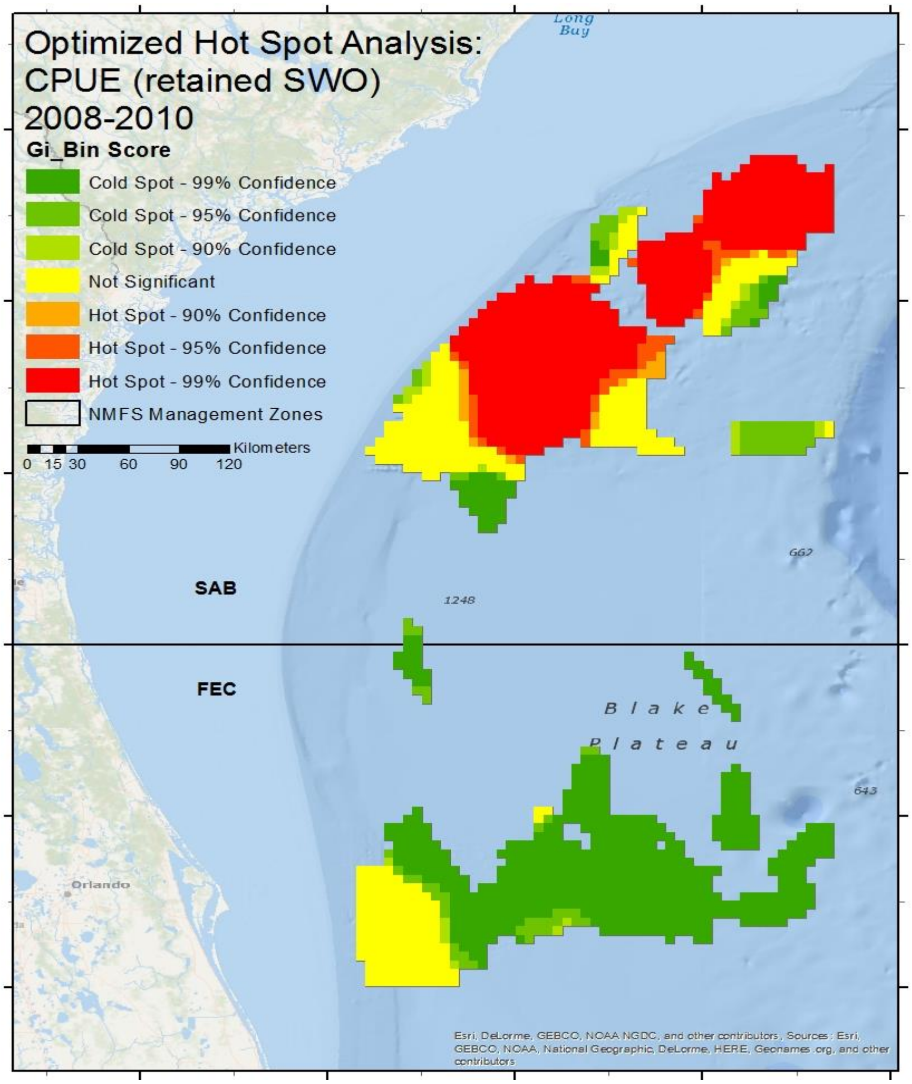


Figure 29. 2008-2010 $^{S}CPUE_{SWOr}$ optimized hot spot analysis in the South Atlantic Bight (SAB) and Florida East Coast (FEC) management zones. Gi_BIN scores are rated -3 – 3, where positive scores reflect hot spots and negative scores reflect cold spots. |1| = 90% confidence; |2| = 95% confidence; |3| = 99% confidence; 0 = not significant (neither a hot spot nor a cold spot). Solid black line delineates boundary between management zones.

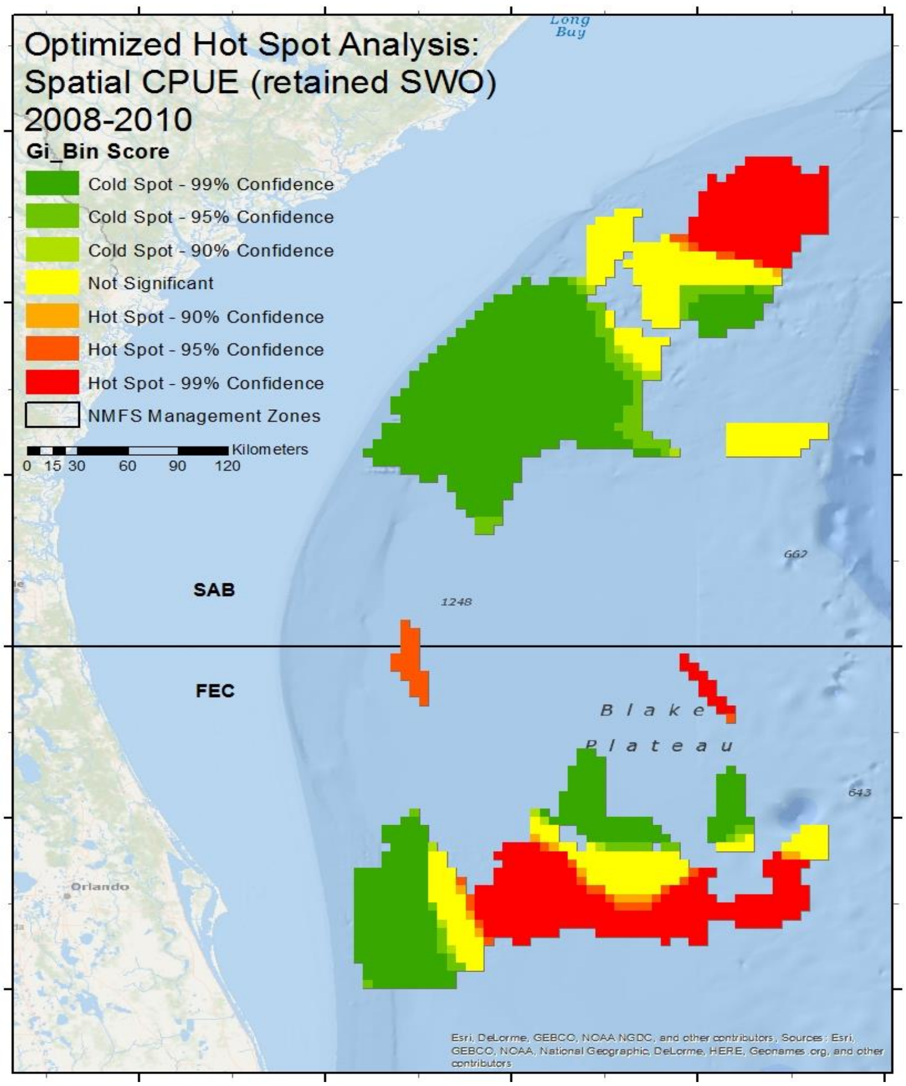


Figure 30. 2008-2010 $CPUE_{BIL}$ optimized hot spot analysis in the South Atlantic Bight (SAB) and Florida East Coast (FEC) management zones. Gi_BIN scores are rated -3 – 3, where positive scores reflect hot spots and negative scores reflect cold spots. |1| = 90% confidence; |2| = 95% confidence; |3| = 99% confidence; 0 = not significant (neither a hot spot nor a cold spot). Solid black line delineates boundary between management zones.

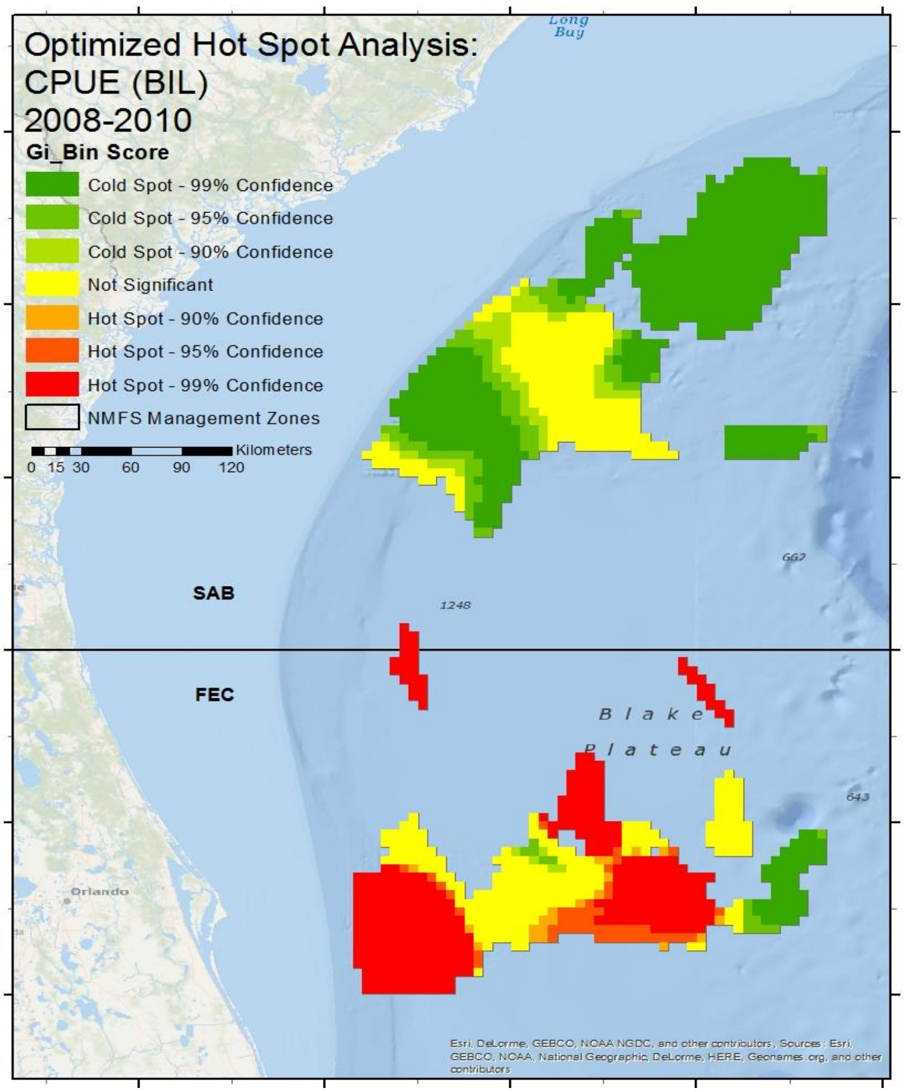
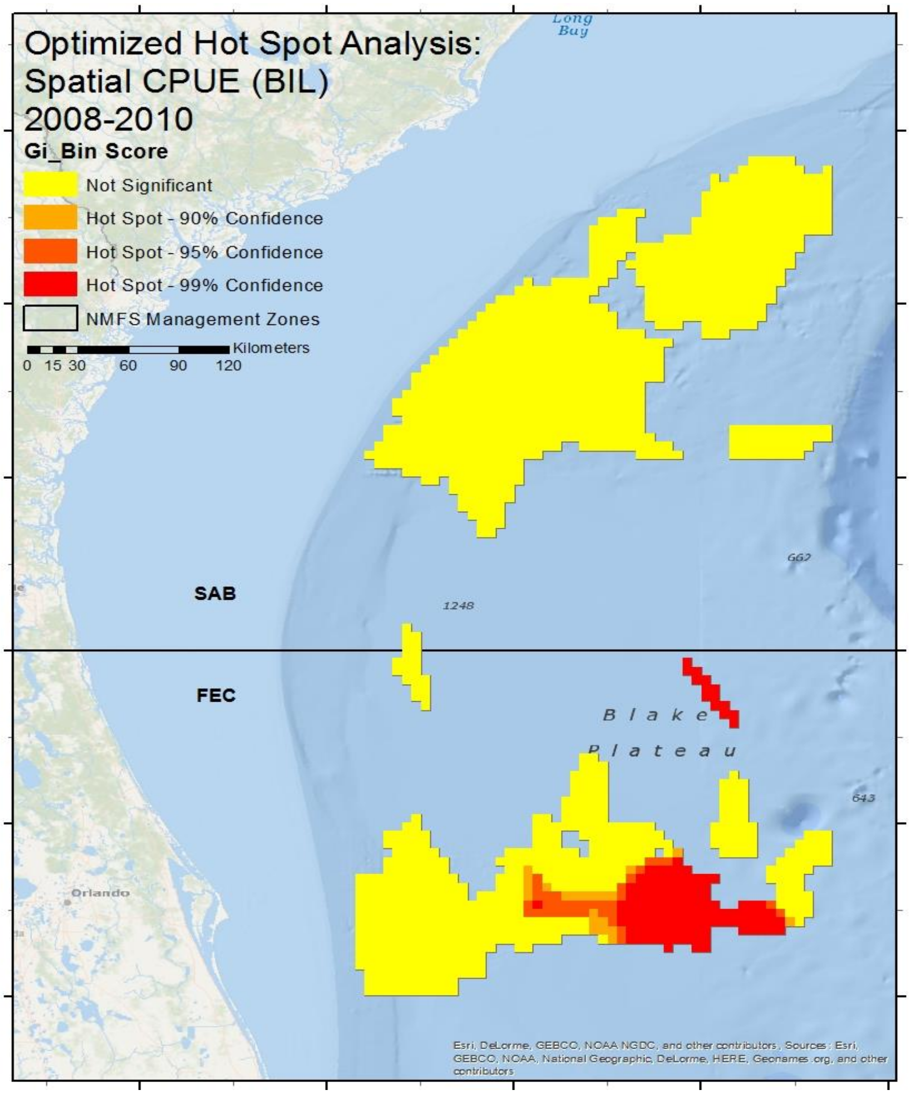


Figure 31. 2008-2010 $^{S}CPUE_{BIL}$ optimized hot spot analysis in the South Atlantic Bight (SAB) and Florida East Coast (FEC) management zones. Gi_BIN scores are rated -3 – 3, where positive scores reflect hot spots and negative scores reflect cold spots. |1| = 90% confidence; |2| = 95% confidence; |3| = 99% confidence; 0 = not significant (neither a hot spot nor a cold spot). Solid black line delineates boundary between management zones.



in each management zone (Figure 31). The smaller hot spot (5,009 km^2) is situated over the northeastward portion of the $CPUE_{SWOr}$ hot spot in the SAB, and the larger one (10,952 km^2) is a narrow band which slightly overlaps the fishing effort hot spot in the FEC on its western boundary and continues eastward across the Blake Plateau nearing the continental slope.

Interestingly, when the 2008-2010 subsets are broken down and examined year by year, the fishing effort hot spot in the SAB disappears (Figures 32A-C). Additionally, instead of a stationary fishing effort hot spot, a westward movement is observed across the Blake Plateau indicating that vessels are concentrating fishing efforts in different locations within the target species geographic range through time. Similarly, $CPUE_{BIL}$ and ${}^{S}CPUE_{BIL}$ hot spots exhibit westward movement across the Black Plateau (Figures 33A-C and Figures 34A-C, respectively). Istiophorid billfish and tunas are generally targeted in epipelagic waters (upper 200 m or 650 ft) and are occasionally seen breaking the surface feeding on shoals of bait fish. Therefore, although not the target species, PLL vessels may gauge the relative movement of billfish as a tool to increase their chances of landing the target species, including swordfish which occupy mesopelagic depths during the day. Adversely, all the $CPUE_{SWOr}$ hot spots were identified in the SAB and were relatively stationary through time (Figures 35A-C).

Figure 32A. 2008 Fishing effort distribution optimized hot spot analysis in the South Atlantic Bight (SAB) and Florida East Coast (FEC) management zones. Gi_BIN scores are rated -3 – 3, where positive scores reflect hot spots and negative scores reflect cold spots. |1| = 90% confidence; |2| = 95% confidence; |3| = 99% confidence; 0 = not significant (neither a hot spot nor a cold spot). Solid black line delineates boundary between management zones.

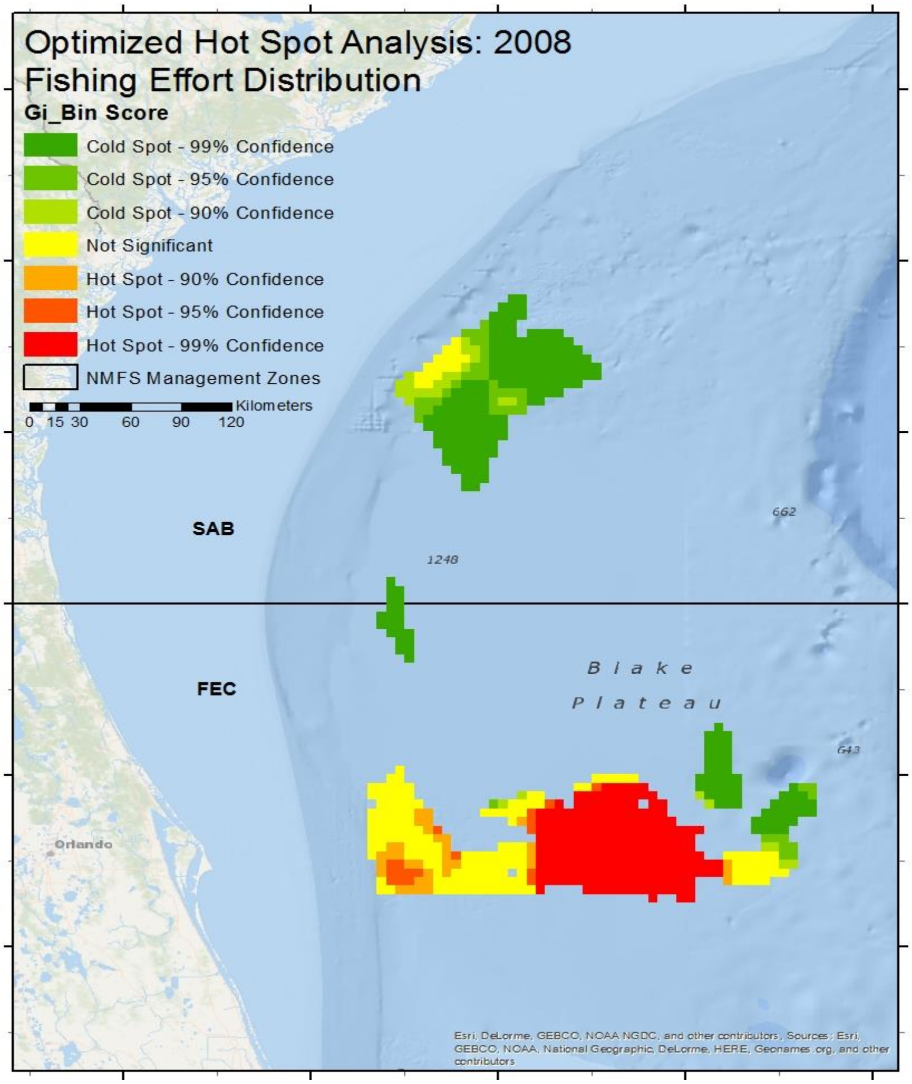


Figure 32B. 2009 Fishing effort distribution optimized hot spot analysis in the South Atlantic Bight (SAB) and Florida East Coast (FEC) management zones. Gi_BIN scores are rated -3 – 3, where positive scores reflect hot spots and negative scores reflect cold spots. |1| = 90% confidence; |2| = 95% confidence; |3| = 99% confidence; 0 = not significant (neither a hot spot nor a cold spot). Solid black line delineates boundary between management zones.

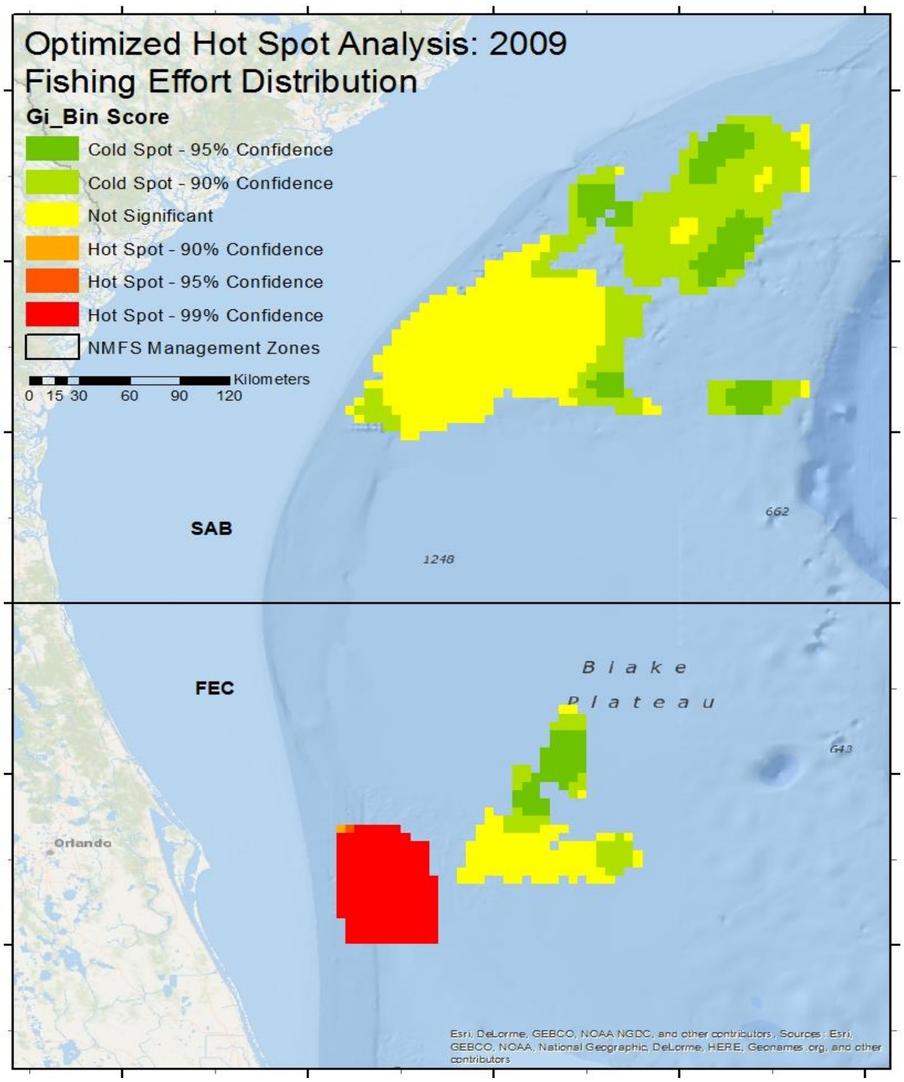


Figure 32C. 2010 Fishing effort distribution optimized hot spot analysis in the South Atlantic Bight (SAB) and Florida East Coast (FEC) management zones. Gi_BIN scores are rated -3 – 3, where positive scores reflect hot spots and negative scores reflect cold spots. |1| = 90% confidence; |2| = 95% confidence; |3| = 99% confidence; 0 = not significant (neither a hot spot nor a cold spot). Solid black line delineates boundary between management zones.

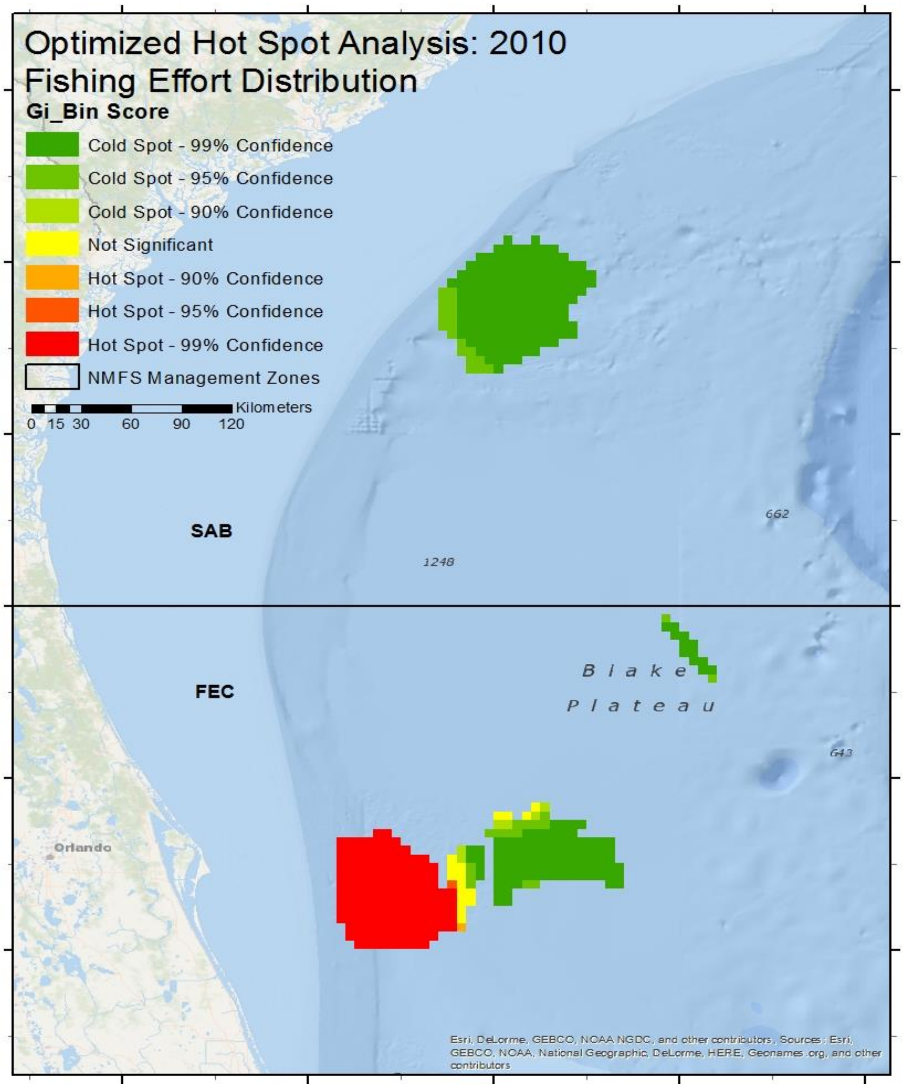


Figure 33A. 2008 $CPUE_{BIL}$ optimized hot spot analysis in the South Atlantic Bight (SAB) and Florida East Coast (FEC) management zones. Gi_BIN scores are rated -3 – 3, where positive scores reflect hot spots and negative scores reflect cold spots. |1| = 90% confidence; |2| = 95% confidence; |3| = 99% confidence; 0 = not significant (neither a hot spot nor a cold spot). Solid black line delineates boundary between management zones.

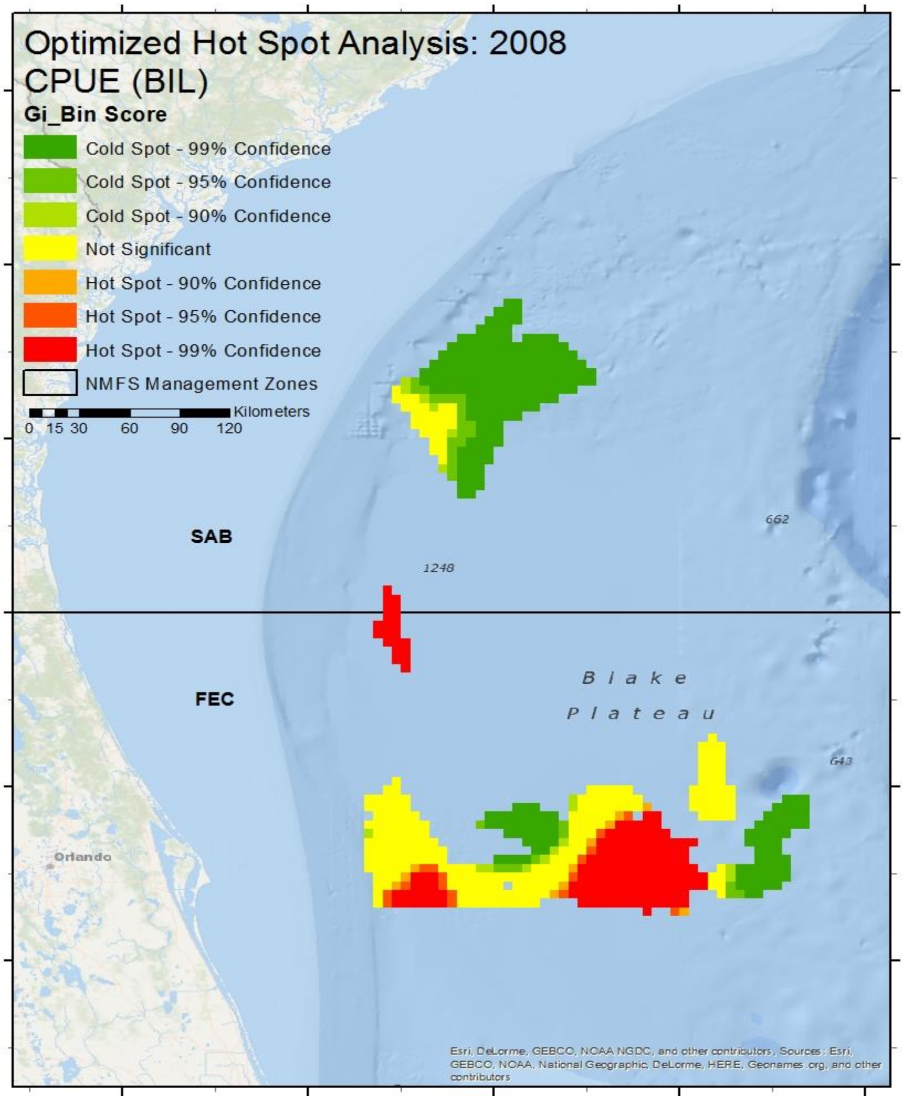


Figure 33B. 2009 $CPUE_{BIL}$ optimized hot spot analysis in the South Atlantic Bight (SAB) and Florida East Coast (FEC) management zones. Gi_BIN scores are rated -3 – 3, where positive scores reflect hot spots and negative scores reflect cold spots. |1| = 90% confidence; |2| = 95% confidence; |3| = 99% confidence; 0 = not significant (neither a hot spot nor a cold spot). Solid black line delineates boundary between management zones.

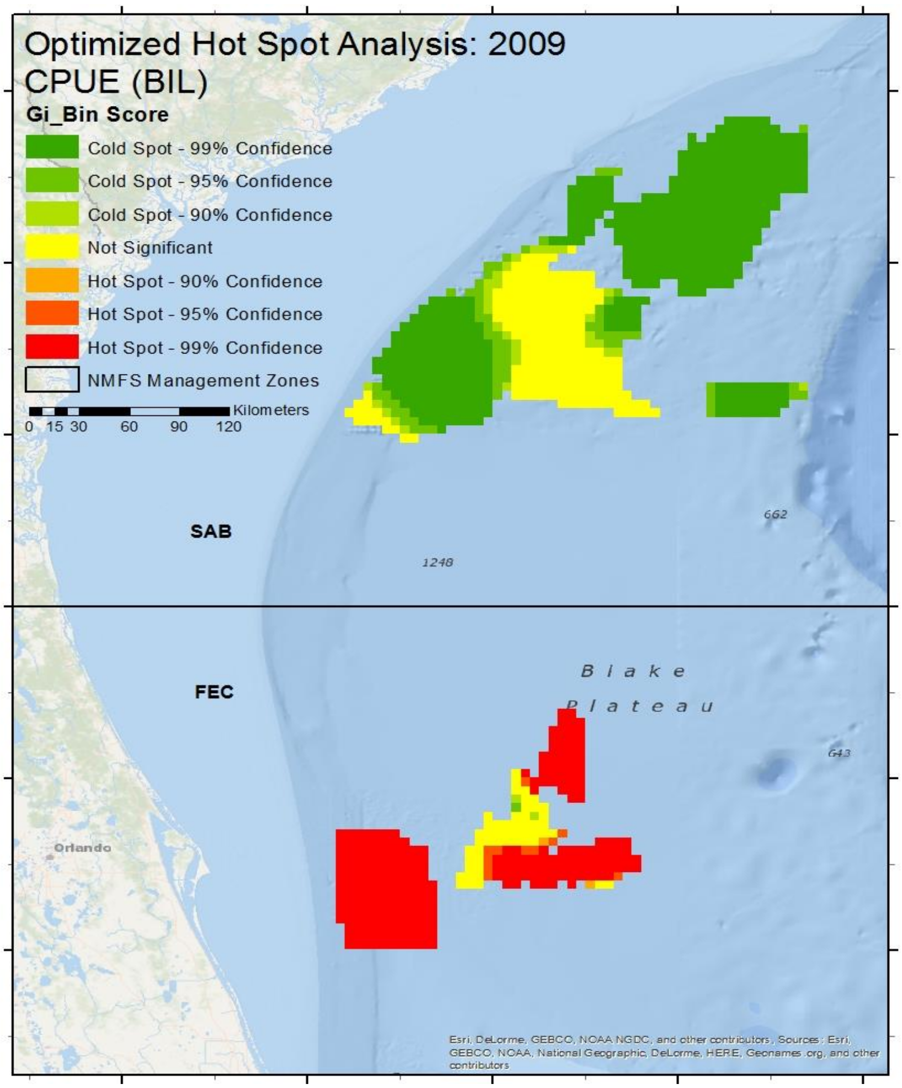


Figure 33C. 2010 $CPUE_{BIL}$ optimized hot spot analysis in the South Atlantic Bight (SAB) and Florida East Coast (FEC) management zones. Gi_BIN scores are rated -3 – 3, where positive scores reflect hot spots and negative scores reflect cold spots. |1| = 90% confidence; |2| = 95% confidence; |3| = 99% confidence; 0 = not significant (neither a hot spot nor a cold spot). Solid black line delineates boundary between management zones.

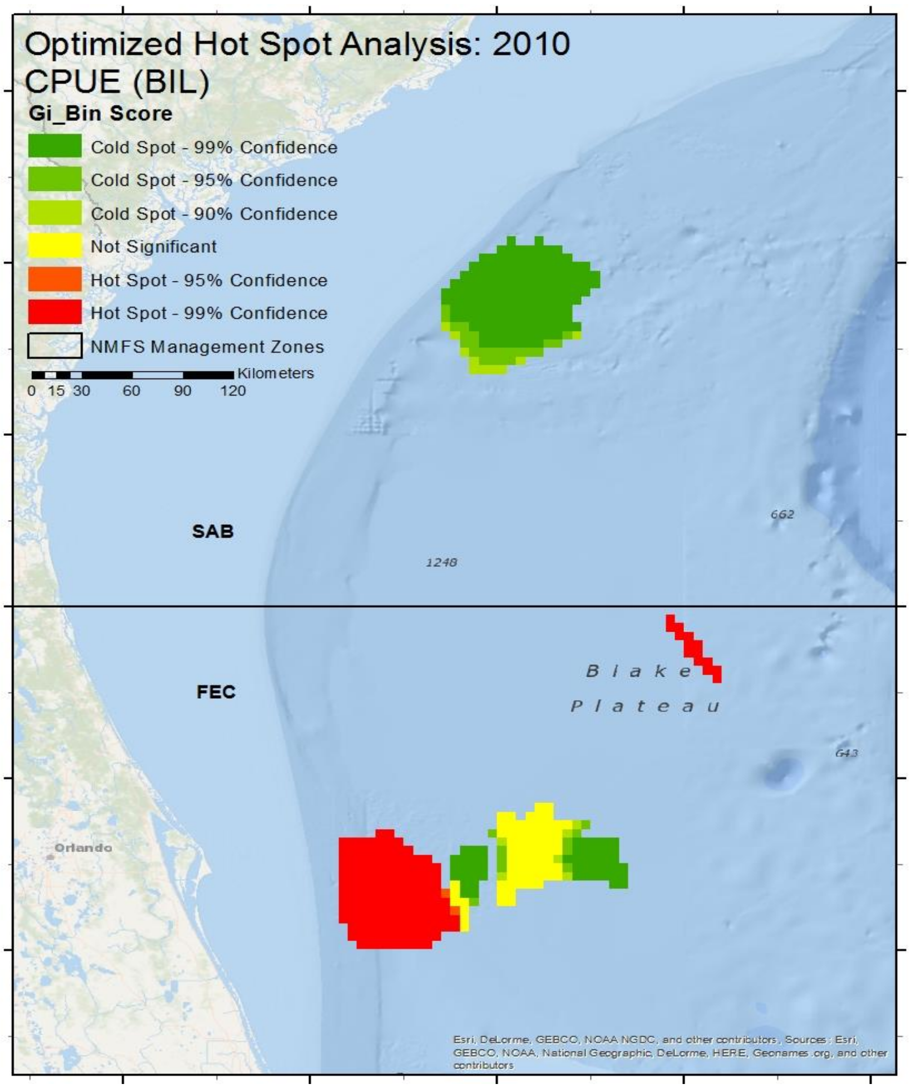


Figure 34A. 2008 $^{S}CPUE_{BIL}$ optimized hot spot analysis in the South Atlantic Bight (SAB) and Florida East Coast (FEC) management zones. Gi_BIN scores are rated -3 – 3, where positive scores reflect hot spots and negative scores reflect cold spots. |1| = 90% confidence; |2| = 95% confidence; |3| = 99% confidence; 0 = not significant (neither a hot spot nor a cold spot). Solid black line delineates boundary between management zones.

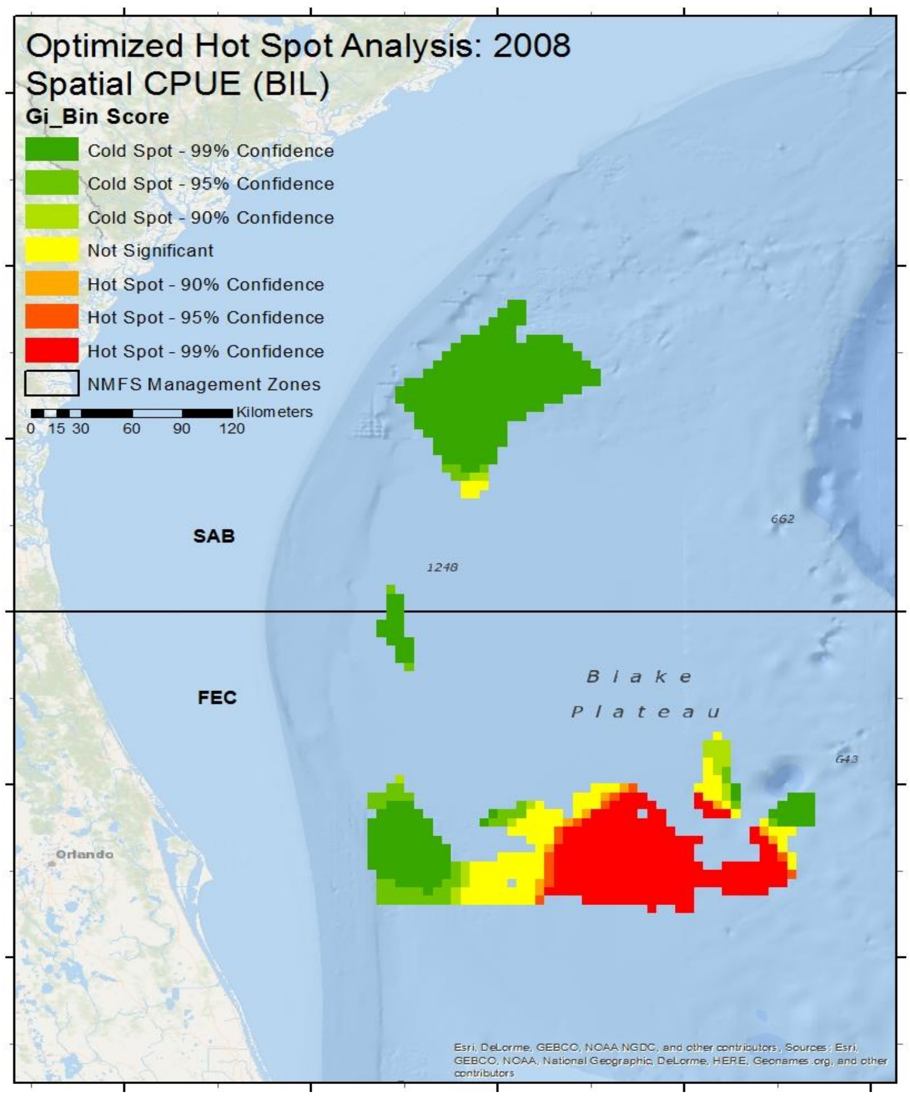


Figure 34B. 2009 ${}^{S}CPUE_{BIL}$ optimized hot spot analysis in the South Atlantic Bight (SAB) and Florida East Coast (FEC) management zones. Gi_BIN scores are rated -3 – 3, where positive scores reflect hot spots and negative scores reflect cold spots. |1| = 90% confidence; |2| = 95% confidence; |3| = 99% confidence; 0 = not significant (neither a hot spot nor a cold spot). Solid black line delineates boundary between management zones.

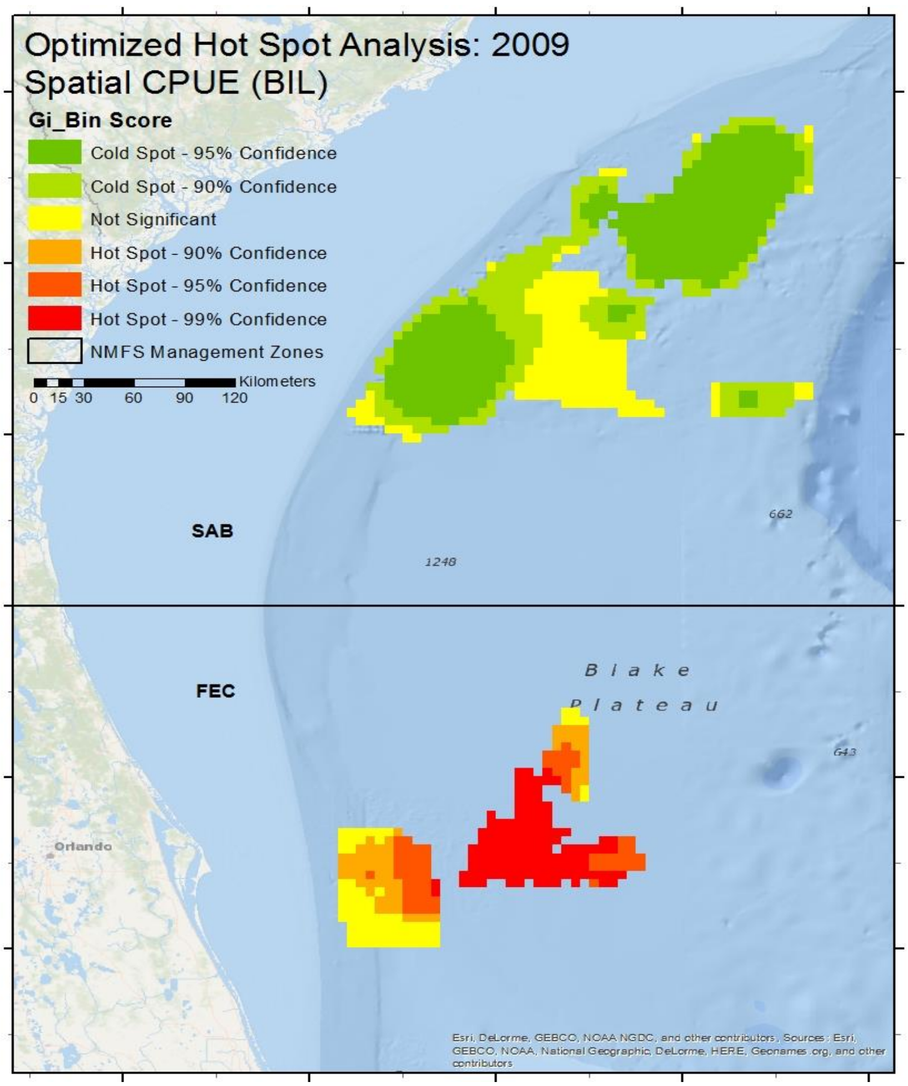


Figure 34C. 2010 $^{S}CPUE_{BIL}$ optimized hot spot analysis in the South Atlantic Bight (SAB) and Florida East Coast (FEC) management zones. Gi_BIN scores are rated -3 – 3, where positive scores reflect hot spots and negative scores reflect cold spots. |1| = 90% confidence; |2| = 95% confidence; |3| = 99% confidence; 0 = not significant (neither a hot spot nor a cold spot). Solid black line delineates boundary between management zones.

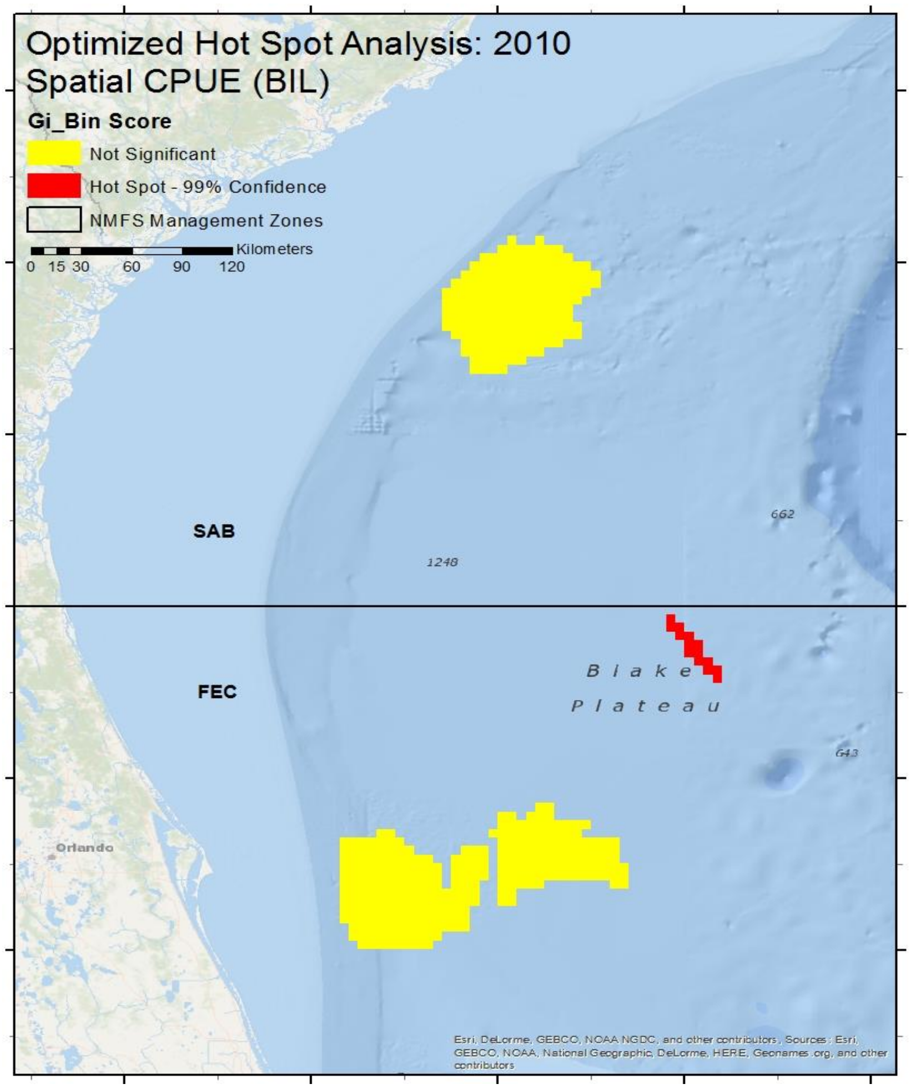


Figure 35A. 2008 $CPUE_{SWOr}$ optimized hot spot analysis in the South Atlantic Bight (SAB) and Florida East Coast (FEC) management zones. Gi_BIN scores are rated -3 – 3, where positive scores reflect hot spots and negative scores reflect cold spots. |1| = 90% confidence; |2| = 95% confidence; |3| = 99% confidence; 0 = not significant (neither a hot spot nor a cold spot). Solid black line delineates boundary between management zones.

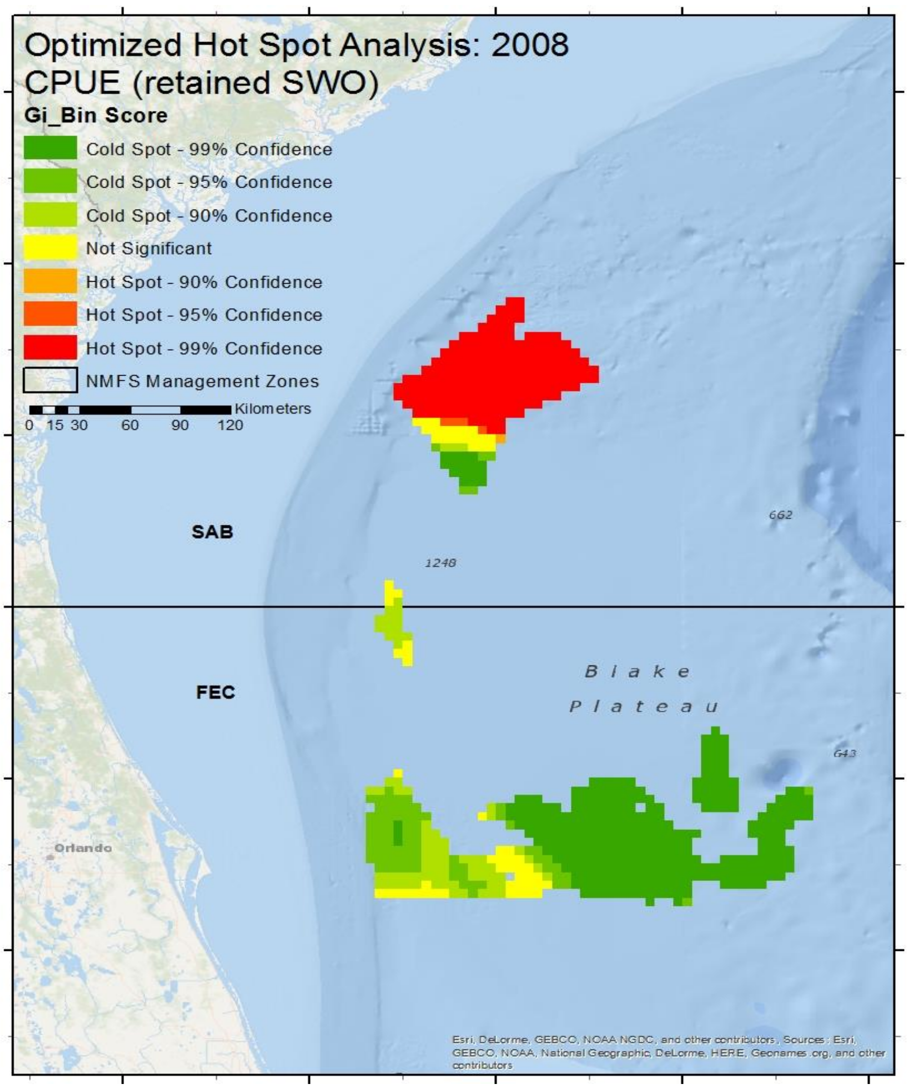


Figure 35B. 2009 *$CPUE_{SWOr}$* optimized hot spot analysis in the South Atlantic Bight (SAB) and Florida East Coast (FEC) management zones. Gi_BIN scores are rated -3 – 3, where positive scores reflect hot spots and negative scores reflect cold spots. |1| = 90% confidence; |2| = 95% confidence; |3| = 99% confidence; 0 = not significant (neither a hot spot nor a cold spot). Solid black line delineates boundary between management zones.

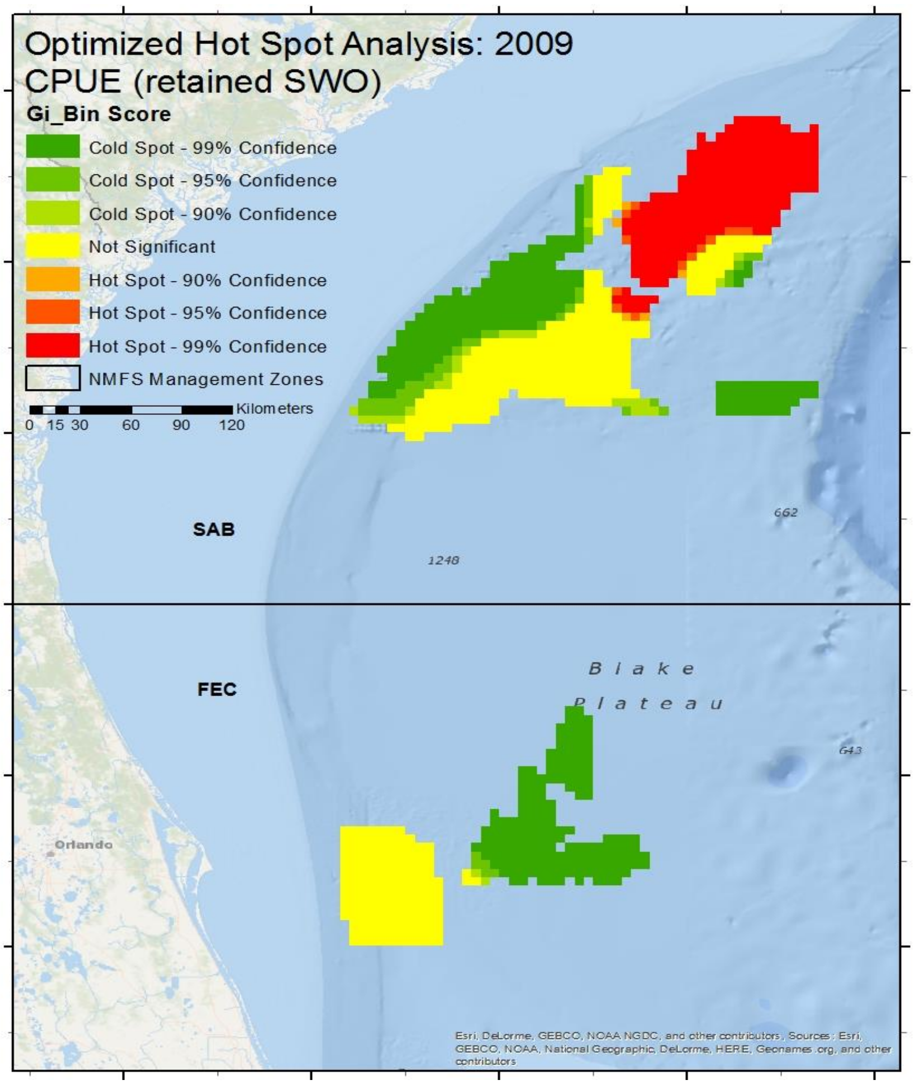
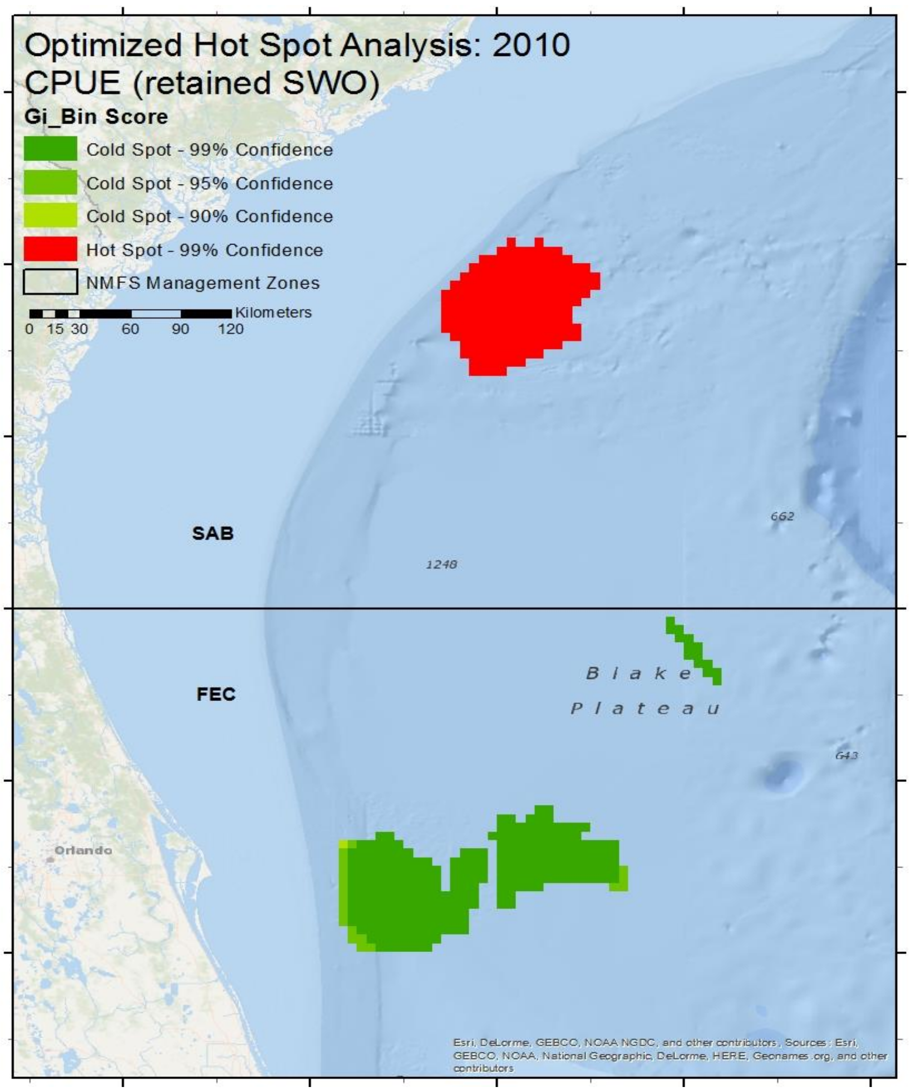


Figure 35C. 2010 $CPUE_{SWOr}$ optimized hot spot analysis in the South Atlantic Bight (SAB) and Florida East Coast (FEC) management zones. Gi_BIN scores are rated -3 – 3, where positive scores reflect hot spots and negative scores reflect cold spots. |1| = 90% confidence; |2| = 95% confidence; |3| = 99% confidence; 0 = not significant (neither a hot spot nor a cold spot). Solid black line delineates boundary between management zones.



Temporal trends in ${}^{S}CPUE_{SWOr}$ hot spots were less obvious and required closer examination. In 2008, the ${}^{S}CPUE_{SWOr}$ hot spot (Figure 36A) was narrow in latitude and nearly spanned across the entire area of observed fishing effort in the FEC. In 2009, that hot spot (Figure 36B) shifted slightly westward and reduced in size. Then in 2010, the hot spot further reduced in size and shifted slightly eastward from its 2009 location (Figure 36C). Additionally, a fair-sized ${}^{S}CPUE_{SWOr}$ hot spot appears in the northward portion of observed fishing effort in the SAB in 2009, and then in 2010 that hot spot substantially reduces in size and migrates southwest along the shelf break. These types of trends reflect the relative shift in hot spot location through time most likely attributed to inter-annual fluctuations in physical and biological parameters, such as ocean currents and plankton blooms. Although the general location of the hot spots are the same (e.g., in waters above the Blake Plateau, or within the FEC), understanding and even anticipating the small-scale changes in hot spot location can have large economic impacts on the fishery.

Figure 36A. 2008 ${}^{S}CPUE_{SWOr}$ optimized hot spot analysis in the South Atlantic Bight (SAB) and Florida East Coast (FEC) management zones. Gi_BIN scores are rated -3 – 3, where positive scores reflect hot spots and negative scores reflect cold spots. |1| = 90% confidence; |2| = 95% confidence; |3| = 99% confidence; 0 = not significant (neither a hot spot nor a cold spot). Solid black line delineates boundary between management zones.

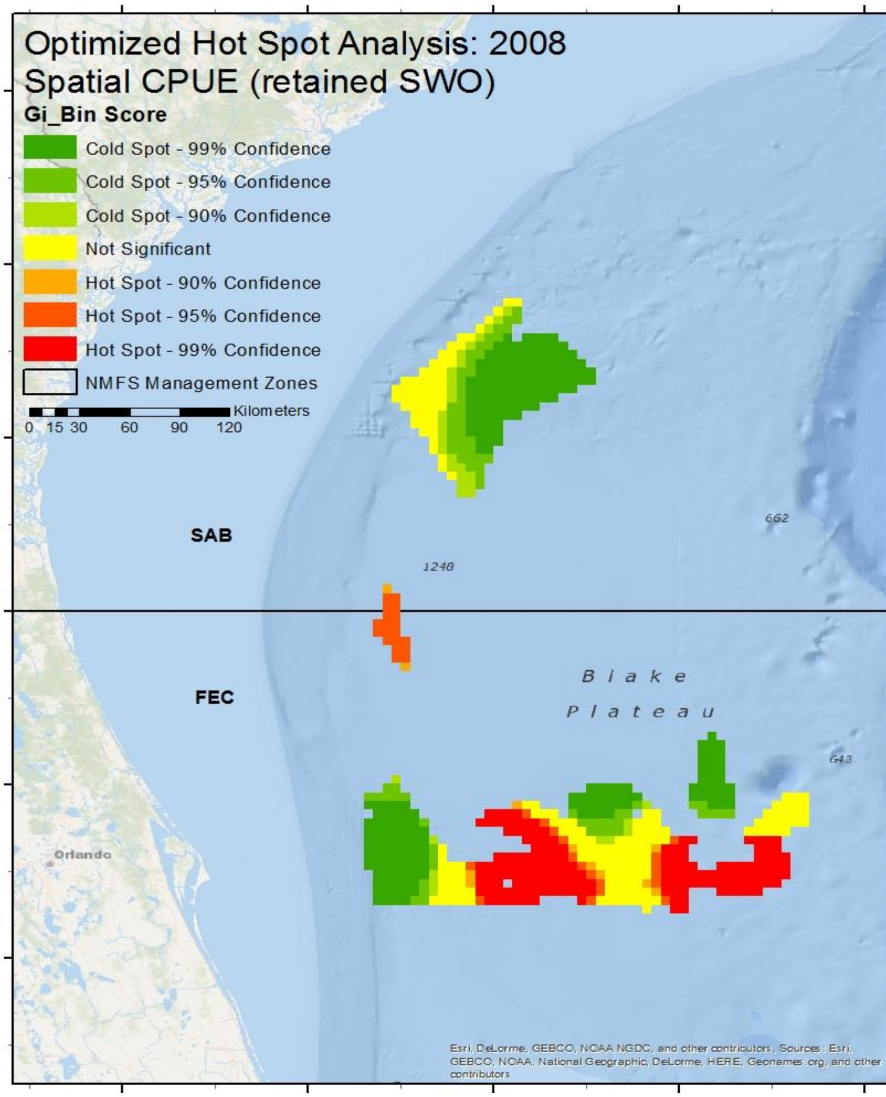


Figure 36B. 2009 ${}^{S}CPUE_{SWOr}$ optimized hot spot analysis in the South Atlantic Bight (SAB) and Florida East Coast (FEC) management zones. Gi_BIN scores are rated -3 – 3, where positive scores reflect hot spots and negative scores reflect cold spots. |1| = 90% confidence; |2| = 95% confidence; |3| = 99% confidence; 0 = not significant (neither a hot spot nor a cold spot). Solid black line delineates boundary between management zones.

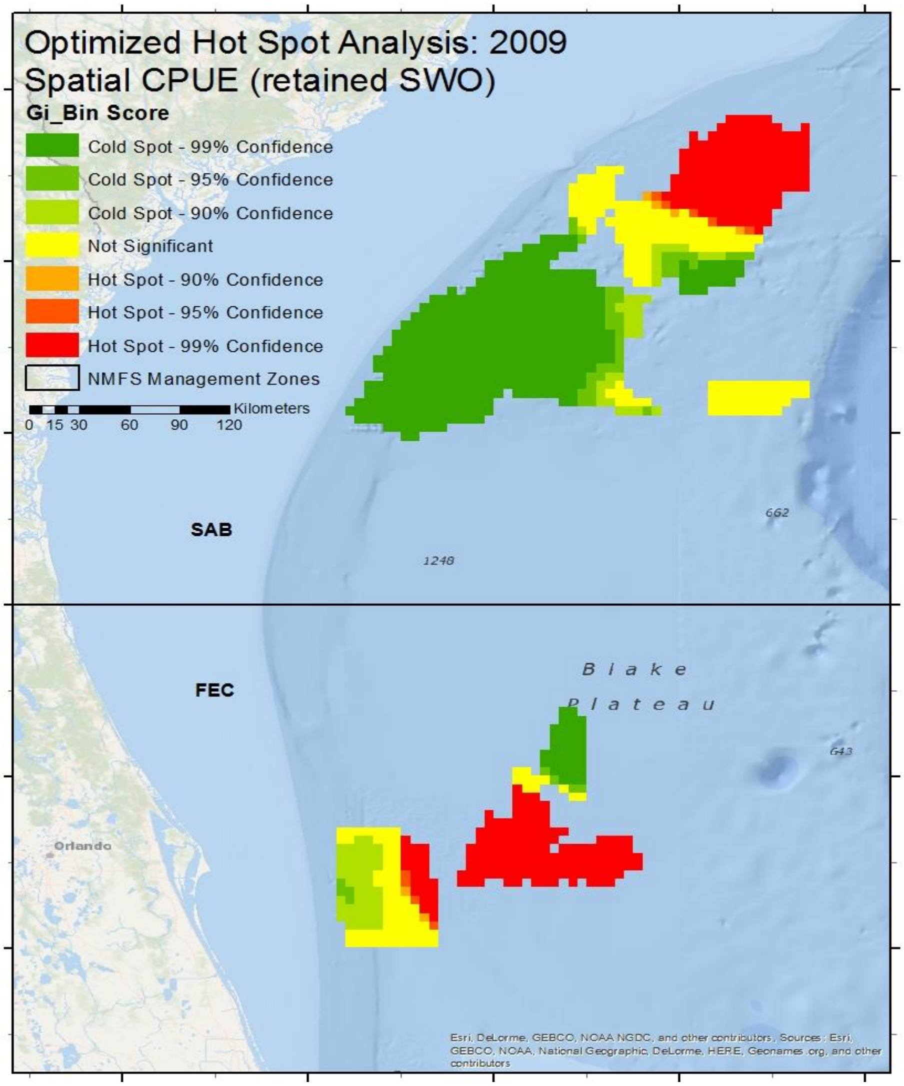
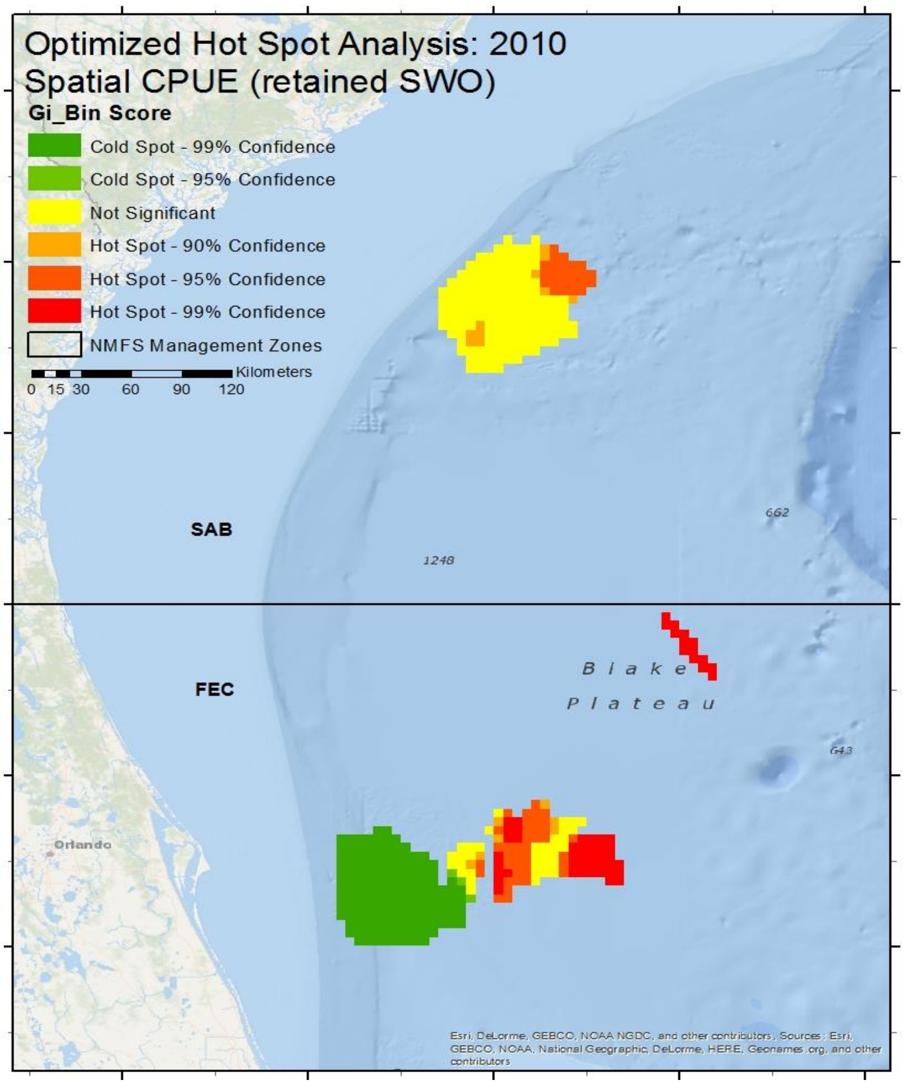


Figure 36C. 2010 $^{S}CPUE_{SWOr}$ optimized hot spot analysis in the South Atlantic Bight (SAB) and Florida East Coast (FEC) management zones. Gi_BIN scores are rated -3 – 3, where positive scores reflect hot spots and negative scores reflect cold spots. |1| = 90% confidence; |2| = 95% confidence; |3| = 99% confidence; 0 = not significant (neither a hot spot nor a cold spot). Solid black line delineates boundary between management zones.



Comparing $^{S}CPUE$ to other spatial CPUE metrics'

Indices of relative abundance (i.e., *CPUE*) have played a pivotal role in fisheries management. HMS fishery management relies heavily on fishery-dependent data because reliable fishery-independent data are costly and difficult to collect (Maunder and Punt 2004). Consequently, multiple standardization techniques have been proposed which attempt to remove or minimize the effects of variables not attributed to abundance. Today, most standardization techniques detect temporal trends in abundance; however, it is widely understood that a true unbiased index of relative abundance must incorporate both temporal and spatial structure (Hilborn and Walters 1992).

Majority of peer-reviewed literature that address spatial and temporal analysis for HMS stock assessments either, (a) attempt to improve current standardization techniques which aim to remove bias introduced by spatial and temporal variation in stock abundance (e.g., Verdoit et al. 2003), (b) incorporate a spatial component into current GLMs (e.g., Nishida and Chen 2004), (c) characterize spatial distribution of a fish population and/or fishing effort from spatially adjusted *CPUE* (e.g., Jurado-Monlina et al. 2011; Langley, 2006), or a combination of these approaches (e.g., Glaser et al. 2011). However, this study is the first to explicitly incorporate a spatial component derived directly from fishing location at the individual set level within the nominal *CPUE* for commercially managed pelagic HMS.

A similar study by Langley (2004) developed a spatially-based *CPUE* for purse seine-captured skipjack from the west-central Pacific Ocean using the following formula,

$$CPUEm = \sum_{i}^{nclust} \left(\frac{catch_{\mathrm{i}}}{effort_{\mathrm{i}}} * area_{\mathrm{i}} * days_{\mathrm{i}} \right) \tag{8}$$

where *CPUEm* is the monthly CPUE index; *nclust* is the number of qualifying clusters in the month (*m*); $catch_i$ is the total skipjack catch (in metric tons) from $cluster_{i,m}$; $effort_i$ is the total number of days fished (including searching) by vessels within $cluster_{i,m}$; $area_i$ is the area (km^2) of $cluster_{i,m}$; and $days_i$ is the duration over which fishing occurred (calendar days) in $cluster_{i,m}$. Here, a cluster analysis was conducted using point data do identify the principal fishing areas for each month. Subsequent *CPUEm* indices were then calculated using the aggregated skipjack catch, effort, area (of the cluster) and fishing days within each qualifying cluster. Therefore, Langley's *CPUEm* metric does not explicitly incorporate spatial data on an individual set level, but rather uses the area of increased fishing effort in the nominal CPUE metric. Additionally, results showed that the magnitude of variation in the nominal *CPUE* indices derived from the same catch and effort data, although similar to *CPUEm* indices, was considerably less. The opposite is observed with ${}^{S}CPUE$ compared to the current nominal *CPUE* (i.e., 95% of ${}^{S}CPUE$ values were < 0.174, max value = 1.73; 58% of CPUE values < 9.58, max value = 95.8). Langley (2004) discusses briefly that the alternative methods described for interpreting catch and effort data are based on the spatial extent of primary fishing location and that further development of this spatially-based approach may lead to a more reliable index of stock abundance. Similarly, the relationship between ${}^{S}CPUE$ and true stock abundance is limited by the spatial extent of observed fishing effort within the species' geographic range.

A second similar study by Courtney and Sigler (2007) analyzed trends in area-weighted *CPUE* of Pacific sleeper sharks *Somniosus pacificus* in the Northeast Pacific Ocean following the methods previously implemented for sablefish longline surveys by Sasaki (1985), Sigler and Fujioka (1988), Sigler and Zenger (1989) and Zenger and Sigler (1992). Here, *CPUE* was calculated as the number of Pacific sleeper sharks caught per hachi (a "hachi" is a standardized unit of effort for the sablefish longline survey and consists of a 100 m line with 45 circle hooks spaced 2 m apart on 1.2 m gangions with 5 m of line left bare on each end of the hachi) for each region (*r*), station (*j*), and depth (*k*). Area-weighted *CPUE* was then calculated primarily using the following equation:

$$RPN_{rj} = \sum_{k} A_{rk} * CPUE_{rjk} \tag{9}$$

where CPUE is multiplied by the estimated bottom area (A_{rk}; km^2) within each region and depth combination for each station and summed across depth strata resulting in an independent estimate of Pacific sleeper shark relative population numbers (RPNs). Station RPNs were then averaged within survey regions to obtain regional RPNs (RPN_r), which were in turn summed within regulatory areas to provide regulatory area RPNs

(*RPN*). Finally, area-weighted CPUE was calculated for standard survey regions and similarly for regulatory areas via equation (10):

$$\textit{Area-weighted CPUE}_{(r)} = \frac{RPN_{(r)}}{A_{(r)}} \tag{10}$$

Although the area-weighted *CPUE* explained above does include an area metric, it does not explicitly incorporate spatial data from the individual set (or hachi) level within the nominal *CPUE* metric (as opposed to $^{S}CPUE$ which does incorporate spatial data directly into the nominal metric).

Management Implications: Stock Assessments, Essential Fish Habitat (EFH) and Areas of Particular Concern

Today, implemented fishery management actions typically follow the results of some sort of stock assessment, and a formal review of all valid recommendations in order to maintain (or increase) fishery sustainability (Hilborn and Walters 1992). *CPUE* is first calculated from catch and effort data and is then used as an index of relatively abundance within various stock assessment models, the results of which are interpreted by fisheries managers to make justified decisions of how to manage the stock. Stock assessments for HMS in the western North Atlantic rely heavily on PLL catch and effort data due to large scale migratory behavior of HMS and because surveys are generally too expensive to conduct (ICCAT 2013). Theoretically, $^{S}CPUE$ is more accurate than standard *CPUE* when used as an index of relative abundance because it incorporates more information about the fishing activity (i.e., spatial data) directly into the nominal *CPUE* metric. Replacing the existing *CPUE* metric with $^{S}CPUE$ as an index of relative abundance within stock assessments would, in turn, likely increase the accuracy of stock assessment results, thus providing the best information available for HMS management.

As mentioned previously, the $^{S}CPUE$ values utilized for optimized hot spot analyses in this thesis were based on the A_f PAF calculation (i.e., four coordinates from the start and end of the full set). Prior to analysis, it was thought that section-level values would further refine the scale and accuracy of $^{S}CPUE$. However, since the majority of the catch usually comes from one or a few sections and is rarely proportional throughout the set, section-level ${}^{S}CPUE$ are extremely variable and can further skew proportionality interpretations when used as an index for relative abundance. However, it is acknowledged that section coordinates do provide a more accurate visual of the area fished by the gear during the soak. Therefore, if captain and observer reporting requirements were to include section coordinates then A_{fs} would be the preferred spatial component for ${}^{S}CPUE$.

Additionally, HMS management groups can benefit from monitoring the spatio-temporal relationship between fishing effort and ${}^{S}CPUE$ hot spot locations. Based on these results, ${}^{S}CPUE$ can be very insightful when delineating boundaries around existing Time-Area Closures (TAC), Marine Protected Areas (MPA), and Essential Fish Habitat (EFH). These hot spots can also help identify potential areas for concern for both target and non-target species that would not otherwise be identified by current spatial representation methods used for HMS management. Historically, animal interactions are spatially referenced using the starting location of PLL sets in which a specific interaction was observed (ICCAT 2013; APLTRP 2014). Since a single PLL set frequently exceeds 30 miles, this method rarely accurately identifies where an interaction took place in space. Using the new ${}^{S}CPUE$, in addition to utilizing spatial information within the metric itself, HMS fishery managers can more accurately identify where an observed animal interaction occurred within the boundaries of the PAF. Therefore, not only could the described methods identify new areas for protection, but fishery managers may also wish to redefine current TAC, MPA, and EFH boundaries.

Conclusion and Future Research

These results are by no means a "silver bullet" for relative abundance indices. For effective fisheries management, ${}^{S}CPUE$ should only be used in the context of other data and information relating to the spatial distribution of fish and fishing effort. The most effective use of ${}^{S}CPUE$ as a tool for fisheries management is unclear and warrants further investigation. As explained by Hilborn and Walters (1992) and reiterated by Langley (2004), if ${}^{S}CPUE$ hot spot results were disseminated to commercial fishermen to better target and avoid particular species, it is likely that fishing effort would become increasingly concentrated in and around the hot spots identified for target species, therefore leading to "hyperstability" interpretations from nominal $^{S}CPUE$ indices. Conversely, if $^{S}CPUE$ hot spot results were retained by fisheries managers solely for monitoring particular areas of concern, then fishermen would not have the best scientific information available in regards to avoiding bycatch and increasing target catch.

$^{S}CPUE$, and subsequent relative abundance indices for HMS, remain heavily reliant on fisheries dependent data. As discussed previously, due to extreme high costs associated with PLL surveys and the highly migratory behavior of these fishes, the lack of fishery independent data sources will likely remain a limitation to HMS stock assessments and successive management actions. A number of other assumptions have to be made when applying the described methods above which are primarily related to changes in catchability and the interactions between fishing fleet dynamics and target species populations. More than likely, these assumptions will be violated to some degree. However, it remains highly probable that $^{S}CPUE$ can significantly reduce the biases introduced when used as an index for relative abundance within HMS stock assessments compared to the current methodology.

The spatio-temporal analyses examined in this thesis are case-specific examples of how GPS data that is currently recorded by all NMFS fisheries observers could be utilized to create a new $^{S}CPUE$ metric thus eliminating the assumption that all parts of species geographic have the same proportion of individuals. $^{S}CPUE$, when used as an index for relative abundance, is more accurate than the conventional *CPUE* because it incorporates spatial information directly obtained from the fishing location. Additionally, $^{S}CPUE$ can be visualized using GIS software to identify hot spots where target and non-target species aggregate. These smaller, more defined hot spots would not have otherwise been identified using the current spatial referencing method for HMS which uses the starting location at the start of PLL sets. It is important to note that fishing effort was not conducted in all locations of the study area, nor was effort conducted equally across all management zones. Fishing effort distribution is a product of accessibility, and captain experience and knowledge of the fishery which is passed on most often by word of mouth. Therefore, complete coverage of HMSs geographic range remains a limitation to HMS management.

The results of this thesis warrant continued research with spatial CPUE, derived from observer based fishery-dependent data, as an index for relative abundance within stock assessment models. However, it would be advisable for NMFS to apply the described methods to their extensive records of archived captain-reported logs and observer data from the western North Atlantic PLL fleet. The results of such an analysis would be applicable to the entire fleet. Additionally, $^{S}CPUE$ indices of relative abundance could be used within current integrated stock assessment models, the results of which could be compared to stock assessment results that use the standard *CPUE* metric. Further still, stock abundance could be forecasted according to various management regimes using $^{S}CPUE$ as an index of relative abundance and compared to current management regimes and stock abundance projections. Inevitably, the results of stock assessment models using $^{S}CPUE$ as an index of relative abundance would most likely differ from current results using standard *CPUE*, thus leading to different management recommendations.

Other research efforts should focus on the spatio-temporal trends in hot spot location with physical parameters including ocean-atmosphere oscillations (i.e., Pacific Decadal Oscillations and El Niño Southern Oscillations), ocean gyres, and smaller scale seasonal parameters such as SST, current speed and strength, and plankton blooms. Examining maps of hot spot location overlaid with remote sensing data (e.g., SST or chlorophyll *a*) for past time periods would provide an opportunity to forecast future $^{S}CPUE$ hot spots and add insight to where vessels will most likely concentrate fishing effort. Various kriging (interpolation) methods may also be applicable for further hot spot analysis to provide information on hot spot location beyond the range of observed fishing effort.

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APPENDIX

I. Trip Summary Log

P C LONGLINE OBSERVER PROGRAM — TRIP SUMMARY LOG — S.E. FISHERIES SCIENCE CENTER

TRIP NUMBER	TRIP TYPE	DEPARTURE DATE mm/dd/yyyy	LANDING DATE mm/dd/yyyy
	☐ Selected ☐ Non Selected ☒ Experimental		

OBSERVER	VESSEL NUMBER	VESSEL NAME

COVERAGE AREA (I)	COVERAGE AREA (II)	COVERAGE AREA (III)	COVERAGE AREA (IV)
☐ Caribbean	☐ Caribbean	☐ Caribbean	☐ Caribbean
☐ Gulf of Mexico	☐ Gulf of Mexico	☐ Gulf of Mexico	☐ Gulf of Mexico
☐ Florida East Coast	☐ Florida East Coast	☐ Florida East Coast	☐ Florida East Coast
☒ South Atlantic Bight	☐ South Atlantic Bight	☐ South Atlantic Bight	☐ South Atlantic Bight
☐ Mid Atlantic Bight	☐ Mid Atlantic Bight	☐ Mid Atlantic Bight	☐ Mid Atlantic Bight
☐ North East Coastal	☐ North East Coastal	☐ North East Coastal	☐ North East Coastal
☐ North East Distant	☐ North East Distant	☐ North East Distant	☐ North East Distant
☐ Sargasso Sea	☐ Sargasso Sea	☐ Sargasso Sea	☐ Sargasso Sea
rth Central Atlantic	☐ North Central Atlantic	☐ North Central Atlantic	☐ North Central Atlantic
☐ Tuna North	☐ Tuna North	☐ Tuna North	☐ Tuna North
☐ Tuna South	☐ Tuna South	☐ Tuna South	☐ Tuna South

SETS OBSERVED (I)	SETS OBSERVED (II)	SETS OBSERVED (III)	SETS OBSERVED (IV)

TOTAL SETS	TOTAL HAULS	TOTAL SEA DAYS

COMMENTS

II. Longline Gear Log

PELAGIC LONGLINE OBSERVER PROGRAM **LONGLINE GEAR LOG** **S.E. FISHERIES SCIENCE CENTER**

OBS/TRIP ID #	VESSEL NAME	VESSEL NUMBER	DATE LANDED mm/dd/yyyy

STRING NUMBER	NUMBER OF HOOKS	ANCHOR ☐ USED? WEIGHT ________ lbs

MAINLINE

COLOR
☐ Clear
☐ White
☐ Pink
☐ Black
☐ Green
☐ Blue
☐ Multi-color
☐ Red
☐ Other

DIAMETER ___.___ mm

TEST ________ lbs

MATERIAL
☐ Nylon
☐ Cotton
☐ Steel Wire
☐ Other

OF STRANDS ________

FLOATS

	NUMBER
☐ Used Polyball	____
☐ Used Bullet/Daub	____
☐ Used Other Floats	____
MAX HOOKS BETWEEN	____
RADIO BEACONS	____
RADAR REFLECTORS	____
NUMBER SECTIONS	____
DISTANCE B/ SECTIONS	___.___nm

LIGHT STICKS

☐ USED?

COLOR
☐ White
☐ Pink
☐ Black
☐ Green
☐ Blue
☐ Multi-color
☐ Red
☐ Other
☐ Yellow
☐ Purple

GANGIONS

COLOR
☐ Clear
☐ White
☐ Pink
☐ Black
☐ Green
☐ Blue
☐ Multi-color
☐ Red
☐ Other

DIAMETER ___.___ mm

TEST ________ lbs

MATERIAL
☐ Nylon
☐ Cotton
☐ Steel Wire
☐ Other

DISTANCE BETWEEN ________ ft

	GANGION LENGTH	GANGION COUNT	LEADERS USED	SWIVELS USED	NUMBER SWIVELS/ GANGION
#1	____ ft	____	☐	☐	____
#2	____ ft	____	☐	☐	____

LEADER LENGTH ________in

LEADER TEST ________lbs

LEADER MATERIAL
☐ Nylon
☐ Cotton
☐ Steel Wire
☐ Other

DROPLINES

	LENGTH	DISTANCE BETWEEN
#1	____ ft	____ ft
#2	____ ft	____ ft
#3	____ ft	____ ft

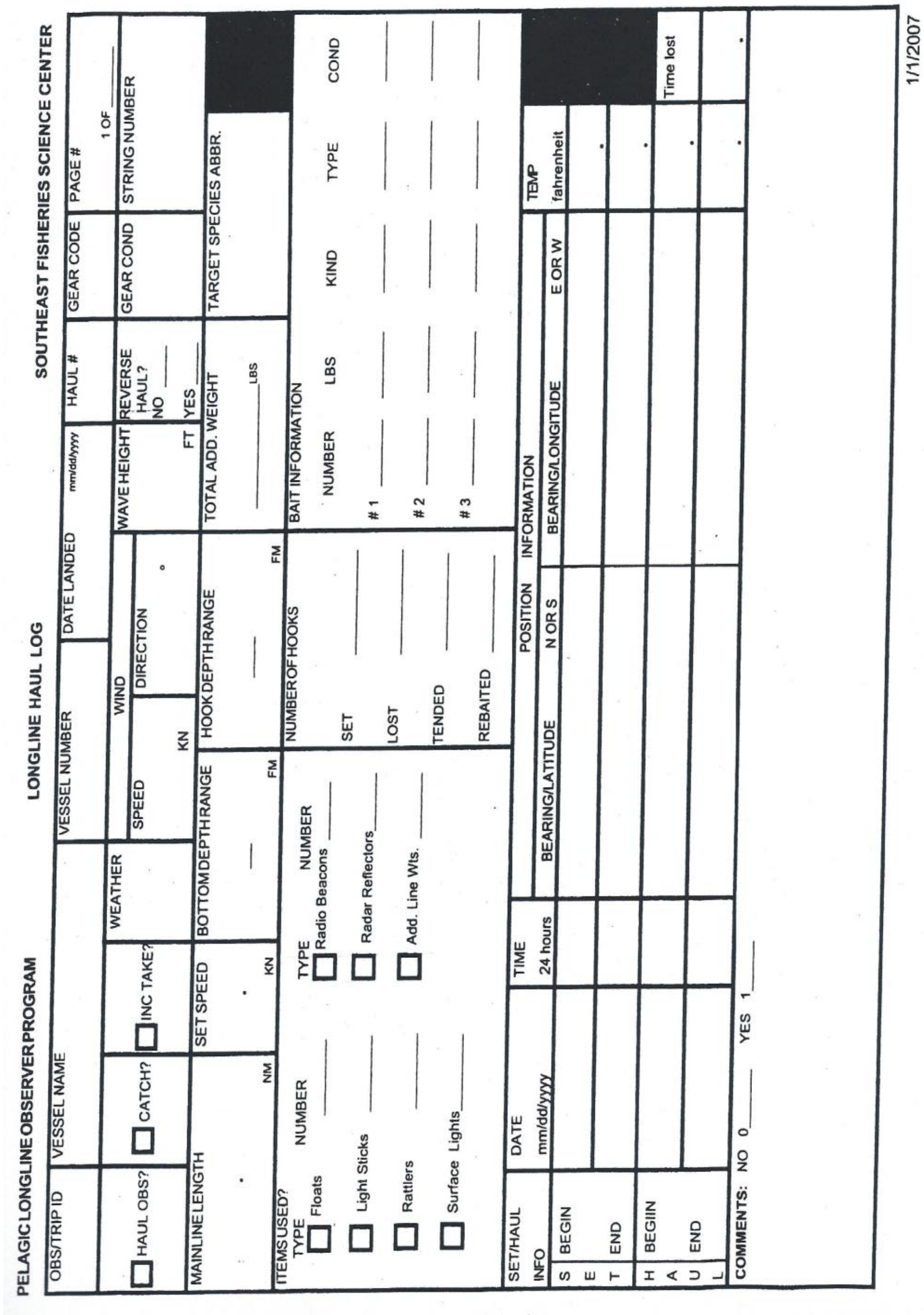
HOOKS

	BRAND	MODEL/PATTERN	SIZE	OFFSET°
HOOK #1	____	____	___/___	____
HOOK#2	____	____	___/___	____
HOOK#3	____	____	___/___	____
HOOK#4	____	____	___/___	____

COMMENTS

02/18/2007

III. Longline Haul Log



PELAGIC LONGLINE OBSERVER PROGRAM — LONGLINE HAUL LOG — SOUTHEAST FISHERIES SCIENCE CENTER

OBS/TRIP ID | VESSEL NAME | VESSEL NUMBER | DATE LANDED mm/dd/yyyy | HAUL # | GEAR CODE | PAGE # 1 OF ____

☐ HAUL OBS? | ☐ CATCH? | ☐ INC TAKE? | WEATHER | WIND: SPEED KN, DIRECTION ° | WAVE HEIGHT FT | REVERSE HAUL? NO ____ YES ____ | GEAR COND | STRING NUMBER

MAINLINE LENGTH . NM | SET SPEED . KN | BOTTOM DEPTH RANGE — FM | HOOK DEPTH RANGE — FM | TOTAL ADD. WEIGHT ________ LBS | TARGET SPECIES ABBR.

ITEMS USED?

TYPE NUMBER

☐ Floats ________

☐ Light Sticks ________

☐ Rattlers ________

☐ Surface Lights________

TYPE NUMBER

☐ Radio Beacons ______

☐ Radar Reflectors______

☐ Add. Line Wts. ______

NUMBER OF HOOKS

SET ________

LOST ________

TENDED ________

REBAITED ________

BAIT INFORMATION

NUMBER LBS KIND TYPE COND

1 ______ ______ ______ ______ ______

2 ______ ______ ______ ______ ______

3 ______ ______ ______ ______ ______

SET/HAUL INFO		DATE mm/dd/yyyy	TIME 24 hours	POSITION INFORMATION: BEARING/LATITUDE	N OR S	BEARING/LONGITUDE	E OR W	TEMP fahrenheit	
SET	BEGIN							.	
	END							.	
HAUL	BEGIIN							.	Time lost
	END							.	.

COMMENTS: NO 0______ YES 1______

1/1/2007

IV. Animal Log

SOUTHEAST FISHERIES SCIENCE CENTER
INDIVIDUAL ANIMAL LOG

02-19-2008

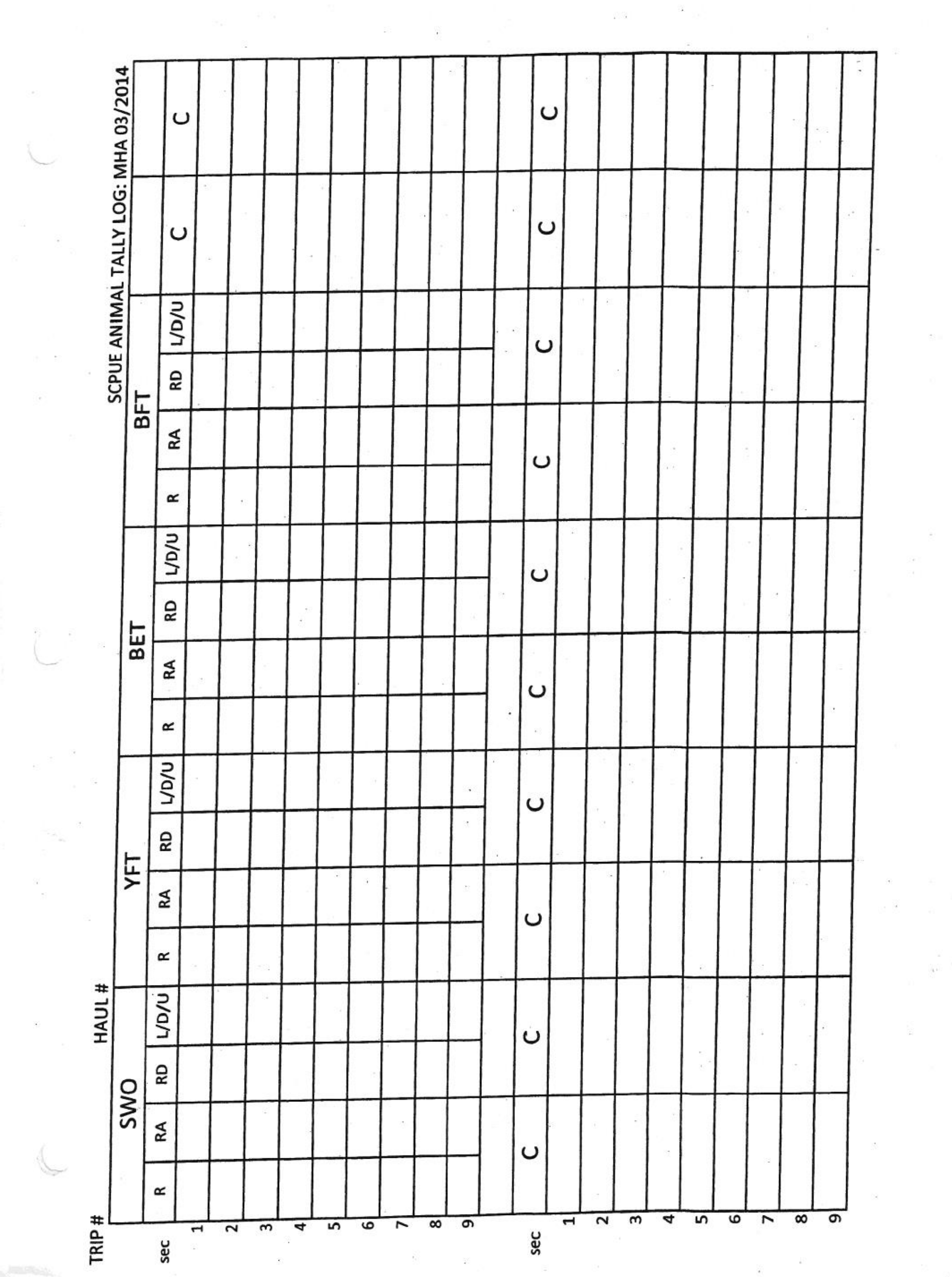
EXPERIMENTAL FISHERY

Obs/Trip Identifier	Vessel Name	Vessel Number	Date of Haul mm/dd/yyyy	Haul Number	Page
			/ /		of

CARCASS TAG or Specimen Number	SECTION	HOOK DEPTH	DAMAGE CD.	SPP. NAME (Abbr)	SPP. CODE (num)	HOOKED? Unknown (0) Mouth hooked (1) Foul hooked (2) Not hooked (3) Gut hooked(4)	STATUS Unknown (0) Alive (1) Dead (2) Damage (3)	ACTION Unknown (0) Kept (1) Released dead (2) Released alive (3) Finned (4) Lost (5) Tended (6)	LENGTH (cm) #1	LENGTH (cm) CODE	DWT (Lbs)	SEX U (0) M (1) F (2)	TAG NUMBER OR SAMPLE OR PHOTO(n) OR COMMENT(r)	TAG CODE TR (1) TT (2) RC (3)	Est. Round Weight (Lbs)

COMMENTS: NO (0)_____ YES (1)

V. Animal Tally Log created for data entry efficiency



SCPUE ANIMAL TALLY LOG: MHA 03/2014

TRIP #

HAUL #

sec	SWO R	SWO RA	SWO RD	SWO L/D/U	YFT R	YFT RA	YFT RD	YFT L/D/U	BET R	BET RA	BET RD	BET L/D/U	BFT R	BFT RA	BFT RD	BFT L/D/U		
1																		
2																		
3																		
4																		
5																		
6																		
7																		
8																		
9																		

sec	C	C	C	C	C	C	C	C	C	C
1										
2										
3										
4										
5										
6										
7										
8										
9										